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ANALYSIS AND EVALUATION OF GERMAN ATTAINMENTS AND RESEARCH IN THE LIQUID ROCKET ENGINE FIELD

VOLUME VII

THRUST CONTROL

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ABSTRACT

This volume on Thrust Control makes an analysis of the various thrust-control systems utilized on both gas-pressure and pump-pressure feed systems and presents detailed analysis, showing both the degree of complication and simplicity which can be achieved depending upon the requirements established for the use of the rocket engine. For a complete coverage of these subjects, it is recommended that all volumes of this series be consulted. Utilization was made of the applicable portions of the 55,000 captured foreign documents relating to rocket engines, supplemented by interrogations of German technical personnel located in the United States.

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ANALYSIS AND EVALUATION OF GERMAN ATTAINMENTS AND RESEARCH IN THE LIQUID ROCKET ENGINE FIELD

PREFACE

This report, Volume VII, entitled "Thrust Control," is one of a series of 14 volumes covering the compilation, resumé, and analysis of German liquid rocket engines, procured from the American Power Jet Co., under Contracts No. W-33-038 ac 17485 and No. AF 33(038)-3636 with the Intelligence Department, AMC, Wright-Patterson Air Force Base, Dayton, Ohio

The 14 volumes of this series are as follows:

Volume I	....	Combustion Chambers
Volume II	....	Combustion Chamber Cooling
Volume III	....	Analysis of Design and Performance of Foreign Rocket Combustion Chambers
Volume IV	....	Propellant Injectors
Volume V	....	Propellant Supply Systems
Volume VI	....	Rocket Engine Turbines and Pumps
Volume VII	....	Thrust Control
Volume VIII	....	Rocket Engine Control and Safety Circuits
Volume IX	....	Liquid Rocket Engine Installation and Flight Program Factors
Volume X	....	Ground Handling of Operational Liquid Rocket Engines
Volume XI	....	Ground Handling of Operational Liquid Rocket Engine Propellants
Volume XII	....	Liquid Rocket Engine Test Facilities and Testing Techniques - Peenemunde Rocket Group
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VOLUME VII

THRUST CONTROL

INTRODUCTION

Requirements for Thrust Variation

In order to achieve a fuller understanding of the problems of thrust control in foreign rocket engines, it is desirable to review the basic parameters involved in the selection of any given thrust or range of thrusts.

The selection of a given thrust value depended upon the mission of the vehicle utilizing the rocket engine, and upon the physical and structural limitations imposed. These requirements were met to varying degrees, depending upon such practical considerations as experience, manufacturing, and available time. The latter factor was of prime importance in dictating the use of simplified, less efficient controls rather than waiting to develop a throttle meeting all specifications.

In general it may be stated that foreign JATO's, ground-to-ground missiles, and flak rockets required constant acceleration, and therefore constant thrust. Many air-to-air or air-to-ground missiles and some ground-to-air missiles demanded a high degree of initial acceleration. For reasons of structural limitation or guidance, however, the acceleration was sometimes limited or even reduced to zero (constant velocity). This was the case in the 109-548, 109-558, and P 3376. On the other hand, rocket engines for piloted aircraft were usually required to have infinite variations of thrust within limits or sets of limits, as in the 109-509 and the P 3390C; this permitted the fullest exploitation of the power available from a rocket when required, together with the conservation of propellant supply.

The specific propellant consumption may serve as an indicator of the rocket engine efficiency. Obviously, high specific propellant consumption is undesirable for high-impulse applications, and is somewhat less critical for those of low impulse. This consideration has a pervasive effect on the type of throttling to be considered. Arrangements for throttling high-impulse systems must give consideration to the resulting variations in specific propellant consumption. For such systems, complicated control procedures are justified if required to maintain engine performance. On the other hand, the differential weight saving in cases of low impulse systems may be so small that considerable decrease in engine efficiency is acceptable, since it would be more than compensated for by lowered cost, complexity, and fixed weight of the engine.

An evaluation of the effect of throttling on specific impulse, as well as the way in which throttling and pump control are interrelated, requires consideration of their respective effects on the fundamental rocket parameters.

I_{sp} is defined as $\frac{F}{\dot{w}}$

w_{sp} is defined as $\frac{1000\,\dot{w}}{F}$

The following factors are found to influence specific impulse:

k = Ratio of specific heats.

$\sqrt{\frac{T_c}{M}}$ = Ratio of chamber temperature to the average molecular weight

Determined by the chamber pressure and mixture ratio.

$\frac{P_c}{P_e}$ = Expansion ratio, determined by the chamber pressure and operating altitude.

The importance of the foregoing parameters follows from the fundamental relationship:

$$F = \dot{m}\, c$$

Since

$$\dot{m} = \frac{\dot{w}}{g}$$

and

$$c = \sqrt{\frac{2gk}{k-1} \cdot R_U \cdot \frac{T_C}{M} \left[1 - \left(\frac{P_e}{P_C}\right)^{\frac{k-1}{k}}\right]}$$

the thrust equation, therefore, becomes

$$F = \frac{\dot{w}}{g} \sqrt{\frac{2gk}{k-1} \cdot R_U \cdot \frac{T_C}{M} \left[1 - \left(\frac{P_e}{P_C}\right)^{\frac{k-1}{k}}\right]}$$

The specific propellant consumption is designated as the weight flow per unit thrust, usually stated in 1000 lb units. For any given thrust, the value of w_{sp} is a function of the exhaust velocity, and hence of k, T_c/M, and P_e/P_c. The latter value is usually taken as the reciprocal of the expansion ratio P_c/P_e.

The functional relationship then appears as

$$w_{sp} \sim \frac{1}{k(T_C/M)(P_C/P_e)}$$

The foregoing discussion emphasizes the dependence of specific impulse upon two general types of factors: combustion phenomena, which depend largely on the propellant selection, mixture ratio, and combustion pressure; and nozzle phenomena associated with the expansion ratio.

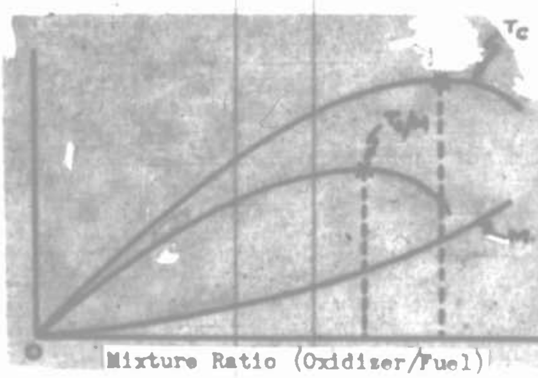
Combustion Phenomena

The effect of mixture ratio on throttling arises from the theoretical considerations relating to the variation of k and T_c/M with changes in mixture ratio. While some propellant combinations have rather poor characteristics in this regard, a reasonably wide range of mixture ratios is permissible without serious diminution of performance with oxygen-alcohol, T-stoff - C-stoff, and "cold" propellant reactions. The need for holding the mixture ratio constant with throttling is present to some degree in all propellant combinations. Consequently, attempts were made to produce variable injectors (100-558), mixture ratio controls (100-708), pressure balancing devices (100-500), etc.

The variation of T_c/M with chamber pressure may be determined from thermodynamic charts and represents changes in available enthalpy drop. In practical cases, the chamber pressure is varied to effect a desired change in thrust according to the relationship $F = C_F P_c f_t$.

Variation in the ratio of specific heats, k, is of secondary importance, as shown in the discussion in the rocket motor theory section of this report (51-0-12A, Vol. I). The commonly used value of k = 1.2 offers an acceptable working approximation. However, tables are available (constructed at Peenemunde) covering the variations of k for oxygen-alcohol, C-stoff-T-stoff, and the "cold" reactions.

A noteworthy point is that the optimum T_c/M is usually obtained below the maximum value of T_c, as illustrated below.



Mixture ratio considerations also affect the injector design. This part of the problem is discussed in detail in the propellant injector portion of this report (51-0-12C, Vol. IV). Nevertheless, it is desirable to note here that a constant mixture ratio requires the maintenance of a constant ratio of pressure drops, and this factor, in turn, influences the design of the thrust control. This conclusion follows from the consideration that the weight flow of any liquid is proportional to to the area (A), the density (ρ), and the square root of the total pressure drop ($K\sqrt{\Delta P}$). To maintain a constant mixture ratio by weight, therefore, it is necessary to hold the ratio

$$\frac{A_o \rho_o \sqrt{\Delta P_o}}{A_f \rho_f \sqrt{\Delta P_f}} = \text{constant}$$

where subscript o = oxidizer
f = fuel

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Cooling is another important consideration in maintaining a good specific impulse during throttling. In practice, combustion chambers are frequently operated at temperatures below the attainable maximum by running the mixture ratio on the fuel-rich side. The additional fuel does not enter into the reaction, and is not influenced by throttling. Accordingly, the method of cooling by fuel dilution results in higher fuel consumption. Thus,

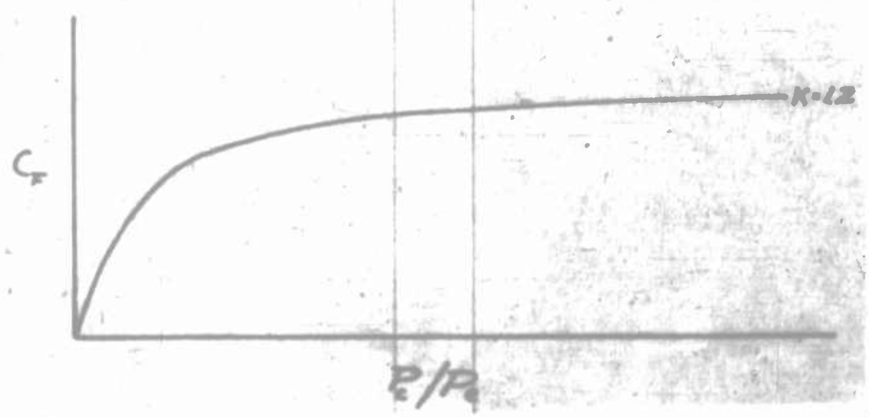
$$W_t = W_c + W_b$$

where W_t = total weight of fuel (not propellant)
W_c = weight of fuel used for cooling
W_b = weight of fuel used in burning

However, the amount of fuel used for cooling depends less on the mass flow through the motor than it does on the chamber surface area. Hence, W_c tends to remain constant throughout the throttling. Therefore, when W_b is reduced because of throttling, W_t does not follow in the same ratio.

Nozzle Phenomena

The expansion ratio, P_c/P_e, is a function of the nozzle design. Conventional theory demonstrates that C_F increases directly as the chamber pressure, and, conversely, declines when the combustion chamber is throttled by dropping the chamber pressure. A secondary consequence follows from the fact that the optimum expansion ratio may no longer be obtained in the nozzle. The importance of these effects depends on the specific chamber pressure selected and on the desired range of throttling. The following sketch displays this relationship.



Variations in the nozzle coefficient convert themselves directly into variations in specific propellant consumption, according to the following relationship:

$$C_F P_c f_t = F = \left(\frac{\dot{W}}{g}\right) c$$

$$\dot{W} = \frac{g C_F P_c f_t}{c}$$

Therefore, as the chamber pressure decreases, lowering the value of C_F, an increase in specific propellant consumption must be anticipated. This relationship applies even if combustion efficiency is maintained, thereby holding the value of c constant.

Among the more interesting innovations in throttling introduced abroad was the idea of compensating for the variation in C_F by holding the chamber pressure constant and varying the throat area (BMW patent application, Sept 1940). In this way, the expansion ratio would be held constant, and hence the value of C_F maintained. A secondary advantage of this arrangement would be the simplification of injector design. This method of throttling is more fully discussed in the following sections of this report.

The operational characteristics of the vehicle sometimes affect the nozzle parameter, particularly where the vehicle must operate through an extreme variation in ambient pressures, e.g., the A-4 and the Wasserfall. Pressure variation appears as the back pressure in the expression, P_e/P_o, and the changes in the nozzle coefficient with this parameter must be taken into account in a successful throttling system.

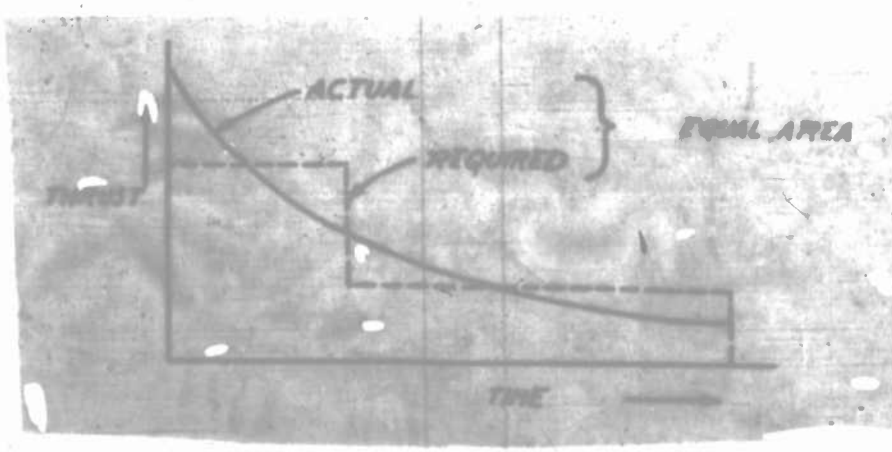
Practical considerations in the design of the nozzle, such as weight, cooling, and aircraft configuration, also influence the obtainable thrust of the vehicle. This is illustrated below in the discussion of thrust control of the 109-509.

METHODS OF THROTTLING

General Types

Three general types of thust control were used in foreign rocket systems: "run-down," set program, and variation at will.

1. Run-Down. Systems throttled by the run-down method were pressure systems used principally in guided missiles. Ground-to-air and some types of air-to-air or air-to-ground missiles, such as the X-4, the E-4, and the R-3, required a high initial thrust to accelerate the vehicle, after which the thrust could be permitted to drop off. Thus, in effect, this method resembles a two-stage throttling system. The run-down pattern closely approximates the thrust requirement of ground-to-air missiles which climb substantially vertically. Since drag is proportional to air density, it decreases with altitude at constant speed. The adjustment of this linear decrease to the adiabatic type of curve characteristic of the run-down method of throttling is made by the fact that the high acceleration required for take-off accounts for the steep portion of the thrust-time curve. The thrust is then permitted to level off, corresponding closely to flight at constant speed. This may be shown in the following schematic illustration.



2. Preset Throttling. This type of regulation attempts more nearly to comply with the missile flight program. It is used where the flight path is determinate, either by preset or remote controls. Four preset types of throttling used are presented.

a. Two-motor operation, in which one motor cuts out after a given time or impulse. Example: the P 3376.

b. Automatic partial shut off of propellant supply. Example: Schmidding SG-24.

c. Constant thrust for take off, followed by variation of thrust depending upon ram air pressure during flight. Example: Hs 117 using the BMW 109-558 rocket engine.

d. Two-stage-thrust operation, obtained by pump-speed variation. Example: the A-4.

3. Variation at Will. A full range of thrust control was required only in military aircraft such as the Me-163, the Me-262, and the Peenemunde rocket interceptor, where it was desired to give the pilot full control over the output of the rocket engine. The high speeds and operational altitudes of Allied bombers and fighters during the last war forced the Germans to design their rocket interceptors for extremes of performance. It was therefore necessary to provide an unlimited control range within the operational limits of the rocket engine. Several degrees of control flexibility were encountered. They may be roughly classified as:

a. Infinite variation. Example: BMW P 3390C and HWK 109-509.

b. Infinite variation within set stages. Example: 109-708B.

THROTTLING OF PRESSURE SYSTEMS

Pressure systems are commonly held to be inflexible with regard to control, and are therefore usually rejected for other than the simplest control requirements. This impression is contradicted by the surprising variety of thrust control patterns encountered in foreign pressure systems. The 109-548 rocket engine was a pressure system with run-down thrust control; the P 3376 had two-stage control; and the thrust of the 109-558 was variable through a wide range of values.

The ability to throttle was found in several types of pressure systems, including conventional gas pressurization, differential pistons, bladder types, and simple orifice types.1/ It is therefore apparent that thrust variation is closely integrated with the over-all design of the system.2/ Certain pressure systems are inherently difficult to regulate, e.g., the differential piston; in others, such as the orifice type, the throttling characteristic is inherent in the basic design; while still others may be varied at will within extremely wide limits.

The Run-Down Method of Thrust Control (BMW 109-548)

The basic principle of the run-down method of thrust control is to use a simple, restricting orifice between the high pressure gas tank and the propellant tanks. In the absence of other regulation, the propellant feed pressure, and hence also the thrust, follow the curve of a polytropic

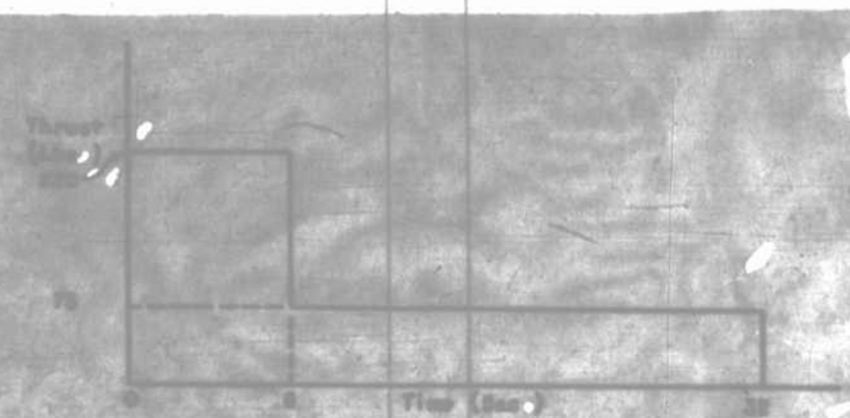
1/ For example, BMW 109-548 pipe coil system.

2/ For design details and analyses of various types of pressure systems, see APJ Report No. 51-0-12H, (Vol. V).

expansion modified somewhat in the direction of an adiabatic curve. The chamber pressure of the BMW 109-548 power plant for the X-4, for example, ranged from approximately 496 psi to 86 psi.

Although providing an inflexible control system, and despite its rapidly worsening specific propellant consumption as the thrust diminishes, this method of throttling has a wide range of application in small-impulse missiles, because their thrust programs are reasonably well met and the decrease in efficiency is more than compensated for by low cost and low fixed weight.

The original rocket engine design for the X-4 missile called for a total impulse of approximately 3520 lb sec. It was divided into two stages, one having 220 lb thrust for 8 sec and the other 73 lb for the remaining 24 sec. This, of course, necessitated the use of a pressure regulator and a special control to reset the regulator after the first 8 sec. To simplify the design, a compromise was made to permit a continually dropping thrust from 330 lb down to the point where combustion ceased at the end of 32 sec. The over-all impulse remained 3520 lb sec. Sketches of the thrust-time curves for the original proposal and the compromised design are as follows:



Original Requirement

Compromise Design

A high initial thrust followed by a rapid drop was necessary in the compromise design, in order to obtain the specified accelerating impulse of 1760 lb sec for the first 8 sec. This, however, subjected the entire X-4 assembly to a high g initial loading, and also required heavy tanks, lines, and motor structure. Moreover, the tubing in the tanks was ruptured by the 1700 psi. To improve this situation, the impulse for the first 8 sec was reduced to approximately 1440 lb sec by lowering the initial supply pressure from 1700 psi to 1560 psi. Although the yield strength of the tubes was still exceeded, this was not considered serious for a "one shot" rocket.

Figure 1 shows the variation of initial thrust and impulse during the 8 sec acceleration period with initial supply pressure. The assumption is made that the pressure tank is filled to 1560 psi at 50°F. Any change in temperature is reflected in the gas pressure according to the formula

$$P_1 T_2 = P_2 T_1 \qquad (1)$$

where P_1 = initial pressure (psi)

T_1 = initial temperature (°F abs)

P_2 = final pressure (psi)

T_2 = final temperature (°F abs)

For example, if P_1 = 1560 psi, P_2 = 1700 psi, T_1 = 512 °F, and T_2 is unknown,

$$T_2 = \frac{P_2 T_1}{} = \frac{(1700)\ (512)}{1560} = 558\text{°F abs}$$

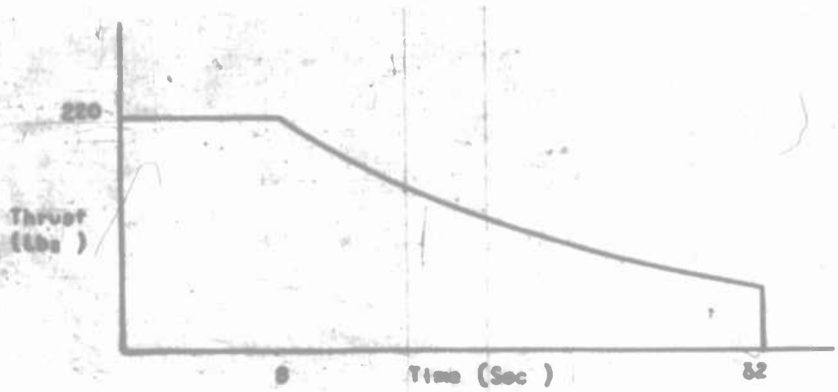
$$\cong \underline{98\text{°F}}.$$

Reference to Fig. 1 confirms this value.

Figures 2 and 3 show the variation of actual and calculated thrust vs. time at 52°F and at -4°F, respectively. As a result of the P-T relationship explained above, the actual thrust values in the lower region on Fig. 2 deviate by as much as 25% from the calculated values, while the actual and calculated thrust values at -4°F coincide quite closely, although the entire curve is considerably below that at 52°F. This, of course, assumes that the gas bottle is filled to its design pressure at 52°F, and that the unit is operated at -4°F. These tests illustrate the close dependence of engine performance on the supply gas temperature. Rocket engines with this type of thrust control should, therefore, compensate for differences between the temperature at which the gas bottle is filled and the operating temperature of the missile. Inasmuch as this factor is a function of operational procedures, provision for field adjustment must be made.

These pressure and temperature limitations had an adverse effect on foreign missile performance. For a while they were regarded as acceptable, in view of the manufacturing ease and simplicity of the 109-548 3/ arrangement. Later, however, proposals were made to improve the impulse by abandoning the pipe coil entirely. Another, less radical proposal, which was never put into production, was to level off the high initial thrust by the use of a simple pressure regulator. The regulator was to be set to limit the thrust to 220 lb for the first 8 sec, after which the gas supply pressure was to decrease to a value which equaled the regulated pressure plus the pressure drop through the regulator. The regulator would demand more supply pressure, which, being unavailable, would cause the regulator to be blocked wide open. The gas pressure would then drop adiabatically through the regulator as if it were a fixed orifice, and the thrust would follow the curve shown below.

3/ Pipe coil system.



The operation of this pipe-coil type of rocket engine is explained in detail in [illegible] Report No. 51-0-12H (Vol. V), but some aspects of thrust control and the effect of decreasing thrust on the specific propellant consumption may here be noted. The value of thrust at any given instant, with efficient combustion assumed, depends upon the supply pressure less the summation of all the pressure drops of the gas and propellants through the tubes, fittings, orifices, combustion-chamber cooling-jacket and propellant injector. The tube sizes, fittings, combustion-chamber cooling-jacket restriction and injector holes were fixed by the detail design parameters.

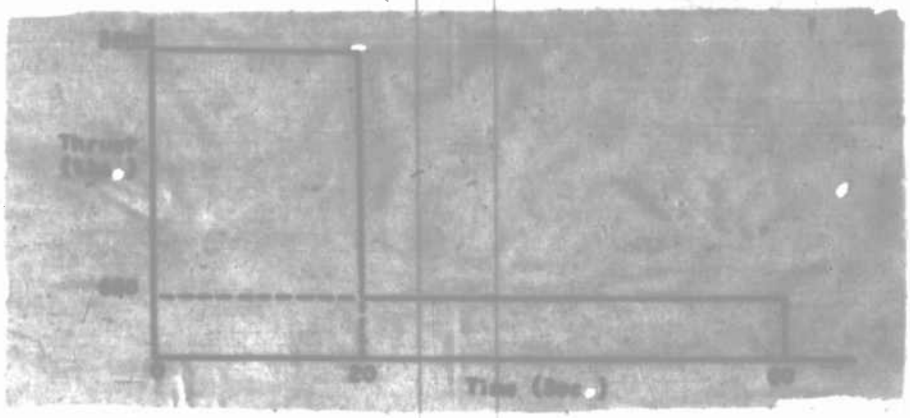
The ignition characteristics were such that it was necessary for the Tonka to enter the motor about half a second earlier than the acid. An orifice in the acid line just before the entrance into the jacket restricted the flow sufficiently to insure the desired time lag. The size of the orifice was determined empirically, and varied between 0.15 and 0.18 in. in diam, depending upon the fabrication tolerances in the various engines. The orifice in the Tonka line just ahead of the injector was also empirically chosen. It was used to lower the Tonka injection pressure to a value comparable with that of the acid after it flowed through the cooling channel. The pressure ratios were controlled in order to maintain the proper mixture ratio of 4.2 : 1 (acid : Tonka) by weight throughout the thrust range.

Figure 4 shows the variation of specific propellant consumption with thrust for three different injectors, compared with the theoretical value (curve 4). Injector No. 3 produced the best results and was the one used in the production model of the 109-548 rocket engine, although over-all experimental research was carried on to the end of the war. As late as November 1944, a proposal was made to design this engine as a bag rocket, in order to increase the total impulse to 4180 lb sec by increasing the tank material strength and the initial pressure. However, no complete unit of this type was ever built. Test units of the pipe-coil design reached the static test stand in August 1944 and flight test units were delivered in February 1945. These proved satisfactory, but the war ended before they could be used operationally.

<u>Preset Throttling by Means of Two-Motor Operation</u> (BMW F3376)

An interesting and simple method of thrust control is that described by BMW in their P 3376 proposal for a differential piston glide bomb, wherein throttling was to be achieved by cutting out one of two motors. One large motor was to produce 2640 lb thrust for the first 20 sec and then be shut off. The smaller, cruising motor was to add 660 lb thrust both during the first 20 sec and for 40 additional seconds. This program would provide the thrust needed for initial acceleration away from the mother aircraft, and for accurate flight control and extended range. The cruising chamber had the further requirement of providing the necessary pressure to operate the differential piston feeding the propellants to both motors.

No specific reference was made to the physical method of cutting off the large motor. One document[4] mentioned that the thrust was a function of impulse. The location of the piston determined the point at which the large motor was shut off. It may, therefore, be assumed that the piston tripped an electrical contact after it had traveled about 57% of its total distance. Solenoid valves or solenoid-piloted servo valves in the propellant lines to the main motor may then have been energized and the propellant supply cut off. The thrust-time curve of the P 3376 may be represented by the following sketch.



Throttling the P 3376 had no ill effect on the quoted specific propellant consumption of 5.2 lb/1000 lb sec impulse.[5] Both chambers were to operate at the same constant chamber pressure, and cutting out one would not adversely affect the other. In fact, the specific propellant consumption of the small motor might improve slightly after the large motor stopped, because less gas would be bled from it to supply propellant feed pressure.

The P 3376 rocket engine never progressed beyond the design stage, not because of design limitations but because other glide-bomb projects received higher priority, and personnel was transferred to the other projects.

If two-stage control of a differential piston rocket unit meets the missile flight requirements, this type of control represents by far the simplest and most efficient method. The specific propellant consumption is not increased; the control may be electrical, mechanical, or hydraulic, and may be set for any desired impulse combinations.

Preset Throttling by Automatic, Partial Shutoff of Propellant Supply (Schmidding SG-24)

An alternative method of securing a preset program was attempted in the Schmidding SG-24. This design cut the flow of propellants and hence throttled the engine, by increasing the pressure drop between the tanks, which were at constant pressure, and the combustion chamber. Thus, substantially the same result was achieved as in the P 3376. The SG-24 was a bag rocket[6] whose thrust was regulated in two stages; one of 330 lb thrust for 4 sec and the other of 110 lb thrust for 25 sec more. A brief description of the rocket engine, shown schematically on Fig. 5 (APJ Dwg. No. 051-900-22-00), is necessary to more fully understand the thrust control.

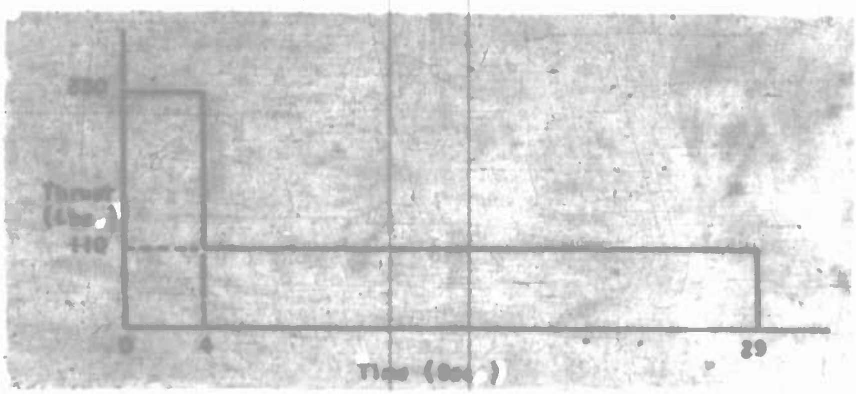
4/ APJ No. F 9-137.

5/ APJ No. F 13-28.

6/ A general discussion of bag rockets may be found in APJ Report No. 51-0-12H, (Vol. V).

The engine is composed of one high-pressure oxygen gas tank (1) and two methyl alcohol-water fuel tanks (2 and 3); the latter (3), which is nearer to the motor (4), is smaller than the other. The gaseous oxygen flows through an electric burst valve (6) after it is energized, and then through a pressure regulator (7), where it is reduced from an initial pressure of 4260 psi to an estimated 430 psi. It then branches into two lines, one of which is led to the top of each of the two fuel tanks, where it pressurizes the fuel by means of the expanding rubber bags. (The bags are used to prevent premixing of the oxygen and the fuel.) The other gaseous-oxygen line branches into two near the motor; one part leads directly into the injector and the other, the larger one, by-passes through a pneumatic, normally open, cut-off valve (5) and then into the injector. The fuel line from the smaller fuel tank (3) incorporates a burst membrane (8) and a ball check valve (9). The line from the larger fuel tank (2) has only a burst membrane (10). The check valve (9) prevents return below from the chamber (4) into the small fuel tank, after its fuel is depleted and the engine is running on the fuel from the large tank alone.

The unit is started by energizing both the main oxygen burst valve (6) and the pyrotechnic igniter (11) simultaneously. The oxygen gas flows through the regulator (7), is reduced in pressure, and flows to the fuel tanks (2 and 3) and the motor (4). The pressurized fuel from both tanks bursts the membranes (8 and 10) in the lines and flows into the injector. The oxygen gas flows through two lines, one through the pneumatic valve (5) into the injector, and the other directly. Ignition takes place from the igniter (11), and a thrust of 330 lb is attained. After 4 sec, the fuel in the smaller tank is depleted, cutting the fuel supply to about one third its former value. For an instant the combustion chamber runs extremely oxygen-rich, but the chamber pressure drops almost instantaneously. This drop closes the pneumatic valve (5) in the oxygen line and cuts the supply of oxygen by one-third, thereby re-establishing the mixture ratio at a lower thrust value. The motor then operates at 110 lb thrust for an additional 25 seconds. The total thrust-time curve therefore, follows the typical two-stage pattern shown below.



It should be noted that the smaller fuel tank has the larger lines, and vice versa. The effect of this arrangement is exactly equivalent to that which would be obtained if a single fuel tank were used with two exit lines in parallel, the larger one being shut off after a short time. 7/ If this alternative had been adopted, however, no simple method of timing would have been available and the respective hydraulic characteristics of the lines would have been difficult to adjust. Accordingly, the arrangement involving two tanks was selected, despite its less favorable surface-volume ratio and hence greater weight.

7/ This arrangement was located in a single reference (APJ No. F 13-91), but appears to have been abandoned for the reasons given here.

No information as to variation of specific propellant consumption with thrust was located. A minimum value of 5.5 lb/1000 lb sec impulse was quoted;8/ this may be taken as valid for the first stage. However, inasmuch as the chamber pressure drops to approximately 33% of its design pressure, the specific propellant consumption during the throttled period may be assumed to have deteriorated to the neighborhood of 6.8 - 7. In view of the relatively longer operating period at the lower thrust, the available specific impulse would be rather poor. However, the total impulse of the system is relatively small, and hence this factor is not too important.

This arrangement may be regarded as relatively poor in comparison with that of the P 3376 described above. However, it will be noted that the maintenance of chamber pressure in the P 3376 was due entirely to the selection of the differential piston system, and could not have been obtained as economically by other means. This point, again, illustrates the design compromises which must be made in the over-all selection of a system.

Preset Throttling by Variable Injector (BMW 109-558)

The ultimate in control flexibility of pressure systems was achieved in the BMW 109-558, which provided for a reliable and sensitive variation of thrust during the flight program. The means chosen to achieve this was by throttling the injector, thereby varying the propellant flow, and hence the thrust. An additional feature of the design arose out of the possibility of maintaining both the mixture ratio and the hydraulic characteristics of the injector. In this way it was hoped to have a system of high efficiency which could also be fabricated in a wide range of impulse. The choice of this method was facilitated by the fact that the 109-558 used the hole-type injector, which permitted a simpler solution than would have been possible with spray or other types.

The BMW 109-558 was intended for application in the Hs-117 flak missile, which was to use a Mach number regulator to maintain a constant air speed. The control was to regulate the thrust smoothly from 836 lb down to 130 lb. Below that point a thrust of 66 lb was maintained by injector holes which were not throttled. This design satisfactorily maintained the flight velocity within ±3% of a Mach number usually quoted as 0.77. 9/

Figure 6 (APJ Dwg. No. 051-950-03-00) shows a schematic representation of that portion of the Mach number regulator affected by static and dynamic pressures. The small triple piston fastened to the bellows' connecting lever acts as a servo pilot valve. Tonka, under pressure, is metered by this pilot to the proper side of the main servo piston and forces it to move. This movement is transmitted by a lever to a gear segment and is transformed into rotary motion. The gear segment meshes with pinions on the injector (explained in detail in the injector section of this report, 51-0-12C, Vol. IV), and rotates the injector throttle. Depending upon the ram and static pressures, injector orifices are cut in or out and the proper missile flight velocity is maintained. Such a regulator must not be influenced by altitude variation. The following calculations demonstrate that differences in static pressure have no significant effect. 10/

Mach number is the ratio of the flight velocity to the velocity of sound at that altitude, and may be expressed by the formula:

$$M = \frac{v}{c} \qquad (2)$$

where M = Mach number
v = flight velocity (ft/sec)
c = velocity of sound at the same altitude (ft/sec)

8/ APJ No. F 13-91.

9/ APJ No. F 5-41.

10/ APJ No. F 5-41.

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The adiabatic head, or the pressure drop in an adiabatic expansion process, in feet of gas, may be expressed as

$$\Delta H_{ad} = RT \cdot \frac{k}{k-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right] \qquad (3)$$

where

ΔH_{ad} = change in adiabatic head (ft) during the process $P_1 \rightarrow P_2$

R = specific gas constant

k = ratio of specific heats = $\frac{C_p}{C_v}$

T = temperature of gas (°F abs)

P_2 = total pressure at the end of the process = P_{tot} (psi)

P_1 = static pressure at the beginning of the process = P_{stat} (psi)

The flight velocity may be expressed by the formula

$$v = \sqrt{2\,g\,\Delta H_{ad}} \qquad (4)$$

where v = flight velocity (ft/sec)

g = acceleration due to gravity = 32.2 ft/sec^2

and the velocity of sound as

$$c = \sqrt{k\,g\,R\,T} \qquad (5)$$

If equation (3) is substituted in equation (4), the resulting value of v divided by equation (5) and substituted for v/c in equation (2), we get

$$M = \frac{v}{c} = \frac{\sqrt{2g\,RT\cdot\left(\frac{k}{k-1}\right)\cdot\left[\left(\frac{P_{TOT}}{P_{STAT}}\right)^{\frac{k-1}{k}} - 1\right]}}{\sqrt{kg\,RT}}$$

$$= \sqrt{\frac{2}{k-1}\left[\left(\frac{P_{TOT}}{P_{STAT}}\right)^{\frac{k-1}{k}} - 1\right]} \qquad (6)$$

If equation (6) is solved for $\frac{P_{tot}}{P_{stat}}$, and the assumed values of M = 0.77 and k = 1.4 substituted therein:

$$\left(\frac{P_{TOT}}{P_{STAT}}\right)^{\frac{1.4-1}{1.4}} = 1 + \left[\frac{(.77)^2}{2} \cdot (1.4-1)\right]$$

$$\left(\frac{P_{TOT}}{P_{STAT}}\right)^{.286} = 1.1185$$

$$\therefore \quad \frac{P_{TOT}}{P_{STAT}} = 1.479$$

By proper proportioning of the lever arms and the balancing piston springs, as shown on reference drawing, and by making a summation of the forces, one obtains:

$$(\Sigma \text{ Vertical}) \; P_{stat} + P_{tot} = P_F \qquad (7)$$

$$(\Sigma \text{ Moment}) \; 1\,(P_{stat}) = 1.479\; P_{tot} \qquad (8)$$

If the P_F spring is loaded to 1.1 lb, this value substituted in equation (7), and equations (7) and (8) solved simultaneously,

$$1.479\; P_{tot} + P_{tot} = 1.1$$

or

$$P_{tot} = \frac{1.1}{2.479} \cong 0.44 \text{ lb}$$

and

$$P_{stat} \cong 0.66 \text{ lb}$$

Identical three-convolution bellows are used to record both the static pressure and the total static plus dynamic pressures. To maintain equilibrium in the "at rest" condition, the P_{stat} bellows is then preloaded to 0.66 lb and the P_{tot} to 0.44 lb, according to the above calculations.

It is necessary to calculate the maximum bellows travel in order to complete the detail design of the regulator. This may be done as follows, by assuming a 0.00787-in. bellows deflection per convolution per 100 mm Hg pressure differential, and by using the German technical value for sea level pressure of 736 mm Hg. The static pressure difference between sea level and 32,800 ft (maximum flight altitude) is then equal to 562 mm Hg.

The bellows maximum travel is determined by

$$S = \Delta P_{max} R_B n_c \qquad (9)$$

where

S = bellows travel (in.)

ΔP_{max} = maximum pressure difference (mm Hg)

R_B = bellows rate per convolution = 0.00787 in. per convolution per 100 mm Hg ΔP

n_c = number of convolutions.

For static pressure:

$$S_{stat} = 562\left(\frac{0.00787}{100}\right)3 = 0.1328 \text{ in.}$$

From equation (8):

$$S_{tot} = (1.479)(0.1328) = 0.196 \text{ in.}$$

To show that the regulator depends solely upon dynamic pressure and is relatively uninfluenced by static pressure changes with altitude, an allowable variation in M of ±2% was assumed. Equation No. (6) was solved for the high and low limits of M, and the value of the ratio P_{tot}/P_{stat} was found to vary from 1.502 to 1.459. It is then evident that P_{tot} may range between two limits for every value of P_{stat}, and this deviation is reflected in a deflection of the metering piston P_F. However, if both values of P_{tot} are calculated for various values of P_{stat}, from sea level to 40,000 ft, the difference, or ΔP, is only 35 mm Hg at sea level, and decreases to 10 mm Hg at 32,800 ft.

The former results in a bellows travel of $35\left(\frac{0.00787}{100}\right)3 = 0.00826$ in., and a metering piston deflection of only $0.00826\left(\frac{1}{2.479}\right) = 0.00334$ in. This is of no importance to the operation of the servo piston and the rotation of the injector head.

Neither the construction nor the operation of the servo piston were located in any of the screened documents. Therefore, in view of the lack of information to the contrary, it may be assumed to be a conventional, high pressure servo actuator, having no special design problems other than proper materials selection. The servo fluid is Tonka, and the seals and gaskets must resist its corrosive action. This is not too serious, as the Hs-117 is a one-shot missile and the seals are not exposed to Tonka until operation has been initiated.

A further advantage of this control is that it acts as a proportional governor; i.e., the further the thrust is from the desired value, the faster the correction is made.

Effect on Engine Performance

Since specific propellant consumption is an indication of the efficiency of rocket engine performance, a graph of the variation of specific propellant consumption with thrust for various altitudes will indicate the relative merit of the individual systems. Figure 7 is a plot of this variation for sea-level operation, for 16,400 ft, and for 32, 800 ft. Values of specific propellant consumption for other altitudes may be obtained by interpolation. At 132 lb thrust the specific propellant consumption is equal to approximately 6.6 lb/1000 lb sec impulse at sea level, and drops to 5 lb at 836 lb thrust. At 32,800 ft, the specific propellant consumption ranges from 5.5 lb at minimum thrust to 4.5 lb at full thrust. The latter value was not confirmed by test; it seems rather optimistic. However, the curves are indicative of the general effect of throttling on specific impulse.

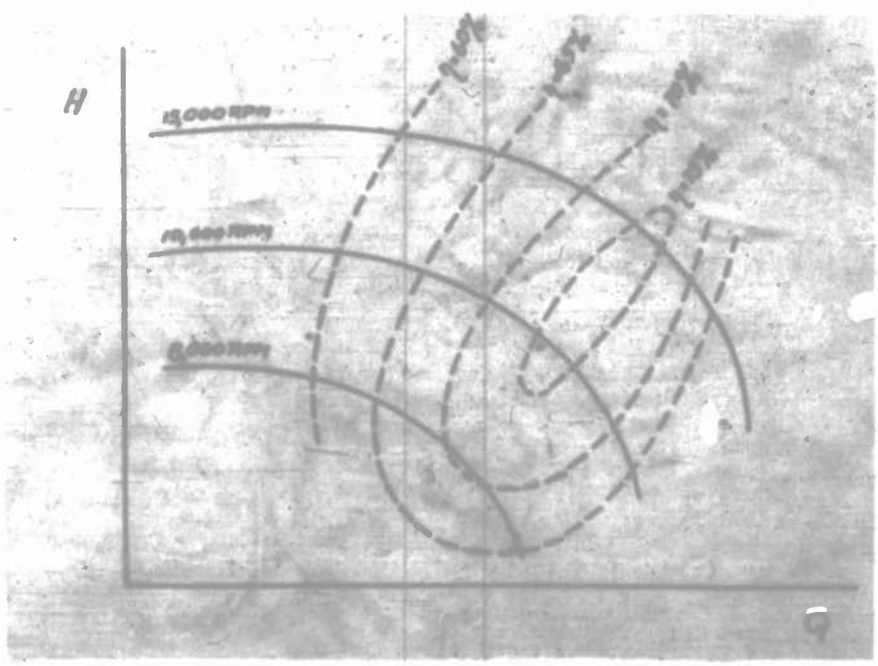
A comparison of the quoted performance of the 109-558 with that of the systems discussed above would seem to lead to the conclusion that injector throttling was a simple and highly efficient means of thrust control. However, the over-all estimates on this point are not clear, since many practical difficulties were experienced with the injector. Inasmuch as the latter is the crux of the design, reliable conclusions on this method must await the accumulation of further test experience.

THROTTLING OF PUMP SYSTEMS

Foreign rocket engines with pump-type propellant feed systems are most frequently encountered in large missiles or in piloted aircraft applications. In both cases requirements for control and operating flexibility lead directly to the requirement for thrust variation. Furthermore, with the exception of a few unusual proposals, all the pumps were of the centrifugal type.

Speed Control

Any analysis of throttling and its effect on pump control must, therefore, be related to the fundamental characteristics of centrifugal pumps. While details are covered in standard handbooks,[11] the fundamental relationships among pressure, quantity, and efficiency may be recalled at this point.



11/ For example, "Centrifugal Pumps and Blowers" by Church, New York, 1944; also "Die Kreiselpumpen" by C. Pfleiderer, Berlin, 1932.

The relations shown above may be expressed by the equations:

$$\frac{H_1}{H_2} = \frac{Q_1^2}{Q_2^2} = \frac{N_1^2}{N_2^2}$$

where H = output pressure head (ft of liquid)
Q = pump output (cfs)
N = pump speed (rpm)

If consideration is now given to alternative means of throttling, described in the foregoing sections of this report, it will be recalled that two general ways of throttling are available: first, by reducing the chamber pressure and the weight flow through the chamber simultaneously; and second, by maintaining the chamber pressure and reducing the weight flow. The former requires no special modification of the combustion chamber, while the latter requires a variation in the rocket combustion chamber throat area, and hence the use of a variable throat plug.

The first alternative, simultaneous reduction of chamber pressure and quantity output of a centrifugal pump, may be achieved in any one of three ways:

1. Pump-Speed Control

This was the most popular form of control, and was used in one way or another in all leading systems, including the P 3390C, the 109-708, and the A-4. Assuming good pump design and a well-matched turbine, it is possible to reduce the pump speed, and consequently the pressure and quantity, while still remaining in an area of relatively high efficiency. In extreme cases of throttling, the pump speed may be reduced to a point where the efficiency is seriously impaired, but in practice this effect need not be of critical importance, since the propellant consumed to drive the pump is a relatively small percentage($\sim 3\%$) of the total.

2. Speed Control Plus Propellant Throttling

The combination of pump speed control with propellant throttling was found in the HWK 109-509. Control of this engine was achieved not only by varying the pump speed but also by restricting the propellant flow downstream of the pump. This arrangement amounts to increasing the pressure drop between the pump and the combustion chamber, hence requiring a higher pump-output pressure for a given throughput than would be the case if pump speed control alone were used. This arrangement makes it possible to remain in a more favorable efficiency region. Also, the absolute amount of work required, hence the steam rate to the turbine, is higher than with pure speed control. The quantitative effects of these relationships must be determined by the interaction between the efficiency and work curves for each specific pump-turbine combination.

3. By-Pass Control

By-pass control involves diverting a portion of the propellant back to the suction side of the pump or to the propellant storage tank. Such an arrangement provides a fairly sensitive means of varying quantity without varying the pump speed, but it is, nevertheless, the least efficient method, because work is done on all of the propellant even though only a portion of it is utilized. Moreover, the propellant is heated during the process, thereby raising its vapor pressure and worsening its cavitation characteristics. An indication of this effect may be found in section 51-0-12G, Vol. V of this report. It is not surprising, therefore, that this system was not encountered in any of the foreign engines analyzed.

In this connection, care should be taken to differentiate the so-called "overpressure by-pass" used in the 109-718 from true by-pass control. The 109-718 by-pass lines were used exclusively to account for small variations in pump output and not for control purposes.

The second major method of throttling, that of constant combustion-chamber pressure with variable throat area, has a varying effect on the pump, depending upon the shape of the P-Q contours. If the pump curve follows the normal centrifugal pattern of a substantially horizontal speed line for the working range, then the effect is to work the pump along substantially constant speed at ever decreasing efficiencies. However, improvements in the combustion-chamber nozzle coefficient, and possibly in the combustion, more than compensate for the decrease in efficiency. Accordingly, this method was proposed in a number of designs, but was never tried because of practical difficulties associated with combustion chamber development.

The throttling arrangement and the method of pump control are both closely integrated with the design of the entire engine. As such, they are influenced to the greatest degree by the mission and the desired performance characteristics. The most instructive method of studying these factors, therefore, appears to be through following some design sequences step by step with a view to evaluating the changes in control in the light of the engine requirements. Accordingly, examples have been selected for each of the types studied: the P 3390C (no less than 11 different versions) and the A-4 developments illustrate pure speed control; the final version of the 109-509 is an example of speed control coupled with propellant throttling. Unfortunately, throttling by throat-area variation was never carried through operational testing, and can be described only by the suggestions made in a BMW patent application.

Development of Control in the P 3390C

The P 3390C was intended as an alternative engine to the 109-509. It was designed to incorporate many of the lessons learned from earlier developments, including the use of two combustion chambers and thrust variation by infinite stages. This engine went through numerous changes in thrust and control requirements, illustrating the range of problems encountered. These are summarized in Table 1, which should be used as a reference key in following the details of the evolution of the P 3390C.

TABLE 1

P 3390C DEVELOPMENT SEQUENCE

Version No.	APJ No.	Proposal Date	BMW Drawing No.	Thrust Values (lb) Cruise	Thrust Values (lb) Climb
1	336	8-43	(RLM Request)	220-880	1100-4400
2	335	8-43	(First Proposal)	220-1100	1100-5500
3a	337	1-44	Sk 1157	220-1100	1320-4400
3b	337	1-44	Sk 1158	220-1100	1320-4400
4	-	1-44	Supplement 124	-	-
5	340	1-44	Sk 1247	330-1650	4400
6	338	2-44	Sk 1246	440-1320	4850
7	-	3-44	Sk 1248	220-1100	1320-4400
8	-	3-44	ERK 12274	220-1100	1320-4400
9	341	4-44	Sk 1297	330-1320	1100-4400
10	342	2-45	109-708B, Sk 1349	330-1100	2970-4400
11	-	4-45	109-708B-1	330-1100	2970-4400

Version Nos. 1 and 2

The original requirements for this engine were set by the German Air Ministry (RLM). Total maximum thrust required of the engine was approximately 5300 lb, with each motor throtteable to

25% of its full thrust value. A gap of approximately 200 lb in the thrust program was regarded as acceptable.

BMW reacted to this suggestion by proposing a system having an unbroken thrust range from 220 lb through 6600 lb. Available evidence indicates that these first two versions never progressed beyond the stage of a preliminary sketch. Development was begun in earnest with the third version.

Version No. 3a Sk 1157, dated 10 January 1944 (See Fig. 8)

Two proposals were developed for the third version, Sk 1157 and Sk 1158. The first system consisted of a cruising chamber with a thrust range of 220 to 1100 lb and a climb chamber of 1320 to 4400 lb thrust, operating at a maximum chamber pressure of 426 psi. Two steam generators were used to drive the pumps; one for the cruise chamber and one for the climb chamber. They were supplied by a hydrogen peroxide pump driven through an overriding gear to the turbine.

Starting was through an electric motor. In this connection it was noted that adverse comment was obtained on the P 3390A as the alternate power plant for the Me-163, on the ground that the current demanded by the starter permitted only one airborne start, in contrast to the five or six permitted by the Walter system. The controls were solenoid-piloted, using hydraulic servo power furnished by a lead from the Tonka pump. Thrust regulation was achieved through rpm control, obtained by coupling the peroxide supply valve to the pilot control. The following tables show pertinent pump and motor characteristics.

Turbine Pump Characteristics

Units	Turbine	Pumps		
		H_2O_2	Acid	Tonka
rpm	30,300	-	15,370	30,300
HP	300	17.2	17.5	73
psi		1060	1135	1135

Combustion Chamber Characteristics

Parameters	Cruising	Climb
Thrust (lb)	220-1100	1320-4400
Pressure (psi)	426 max	426 max
Propellant Consumption (lb/sec)	5.61	22.9

The following is the order of operation:

1. Close main switch (3). Current passes through only if the pilot stick is at zero.

2. Relay cuts in starter motor, causing pump for H_2O_2 to run. The turbine still does not rotate, since there is a free-wheeling coupling between starter, H_2O_2 pump, and turbine.

3. Pressure in the peroxide line to the regulator valve (A) rises.

4. Opening of the regulator valve (A) by the pilot stick permits H_2O_2 to flow to the steam generator of the cruising combustion chamber (steam generator). The turbine starts up and overtakes the pump free wheel clutch (B). Pressure in the peroxide line rises and cuts out the starter (C), probably by way of line (7).

5. Now the pressure rises in the propellant lines. When the pressure in both lines has reached the proper value, the pressure switches (12 and 13) close, automatically opening the starter valves for the cruising combustion chamber by means of the solenoid switch (14).

6. The cruising combustion chamber operates at 220 lb thrust. By further opening of the regulator valve (A), the speed and pressure are at first increased; then, by means of the selecting switch (D), the second valve in front of the cruising combustion chamber is opened electrically by the solenoid switch (16).

This double switching was probably intended to serve the purpose of avoiding too large a drop in speed in the lower operative region of the turbine, where its excess output is small compared with the power requirements of the pump. Now the cruising combustion chamber can be brought up to its highest value of 1100 lb.

7. When the regulator valve is opened further, valve (18) of the second steam generator is also switched in by the selecting switch (D). Steam pressure actuates the switch (19), which electrically opens valve (20) of the climb combustion chamber.

8. Owing to the foregoing operations, the thrust of the climb combustion chamber (1320 lb) is added to that of the cruising combustion chamber (1100 lb). However, since the pressure decreases because of the increased demand on the pump output, an unknown thrust value will result here.

9. Further opening of the valve (A) increases the steam generator supply and the turbine speed, and the thrust may go to its maximum of 5500 lb.

10. If the propellant pressure drops (in an emergency), the electrical pressure switch (17) cuts off all the solenoids, which shuts all the valves.

<u>Version No. 3b Sk 1158 (See Fig. 9)</u>

This schematic was drawn up approximately a week later than Sk 1157, and represents a notable complication of control.

1. The relief valve before the regulator (38) is replaced by an electrically operated solenoid valve (11). There also is a controlled H_2O_2 by-pass which avoids the regulators.

2. A safety switch (10) has been added, which shuts off the entire system if a pressure higher than 1135 psi is attained.

3. A short circuit line (39) is cut off when the climb chamber is switched in, eliminating the operation of the by-pass line. It should be noted that the solenoid-operated pilot valves are not always drawn in their correct position. The drawing should, therefore, be used with caution.

4. The following thrusts are available:

Cruise Chamber	220 - 1100 lb
Climb Chamber	1320 - 4400 lb.

The control region is given as 220 to 1100 lb thrust for the cruise chamber and 1540 to 5500 lb for the climb. It may be assumed from this that when the climb combustion chamber is switched on, both chamber pressures drop to the value obtained at the start. Thrust is then recovered by increases in pump speed consequent on the increased output of the steam generators.

Version No. 4 Supplement 124

This represents the comment of the research section (ERF) on the designs previously presented by the design office (ERK). ERF opposed the complicated controls and the electrical switching equipment in Sk 1158. Extremely simplified hydraulic and electrical schematics were presented. It was suggested that the following changes be made in schematic Sk 1158.

1. Eliminate the cutoff valves in the peroxide line before both regulator and steam generator.

2. Eliminate the cutoff valves for the Tonka and acid.

3. Operate valves using H_2O_2 as the servo fluid. This is particularly hazardous suggestion, in view of peroxide properties and of the need for piping the hydrogen peroxide for long distances.

4. Eliminate most of the safety devices, including under- and over-pressure switches.

5. By eliminating the double "line switching" in the cruising chamber, simplification is achieved.

6. Eliminate the by-pass lines around the regulator (39).

Many of these suggestions appear to be on the risky side. However, these ideas had a corrective influence on the complexity of the preceeding version.

Version Nos. 5 and 6 Sk 1247 and Sk 1246, dated January and February 1944

The suggestions in Version 4 formed the basis for simplifying proposals which, however, had a definite effect on the controllable thrust range. The large combustion chamber was not throttable in these arrangements, and only the small chamber could be varied. The justification for this change arose from calculations of Me-163 performance which disclosed that the climb chamber would be required at full thrust or not at all, and maneuvering requirements could easily be met with the cruise chamber. In this connection, however, it is worth noting that the maximum thrust was brought up from 1100 lb to 1650 lb. These suggestions, in common with the earlier units, had a throttling range of about 4:1.

It appears that these proposals did not meet with favor at the German Air Ministry, since the succeeding versions reverted to the throttling of both combustion chambers in an effort to provide a throttling range as continuous as possible. In view of the urgency of the German military situation in April 1944, this decision does not appear to have been a wise one, since the additional work required to control both motors imposed further delays on the development.

It may be conjectured that if the design had been frozen at this point and full use made of components developed for earlier engines, a fully operational unit might have been obtained by approximately November 1944. This lack of realism, however, seems to have characterized a large portion of German rocket research activity.

Version No. 7 Sk 1248, dated March 1944 (See Fig. 10)

The revised arrangement of the P 3390C appears to have undergone considerable improvement as a result of the train of ideas presented in Versions 4, 5, and 6. The basic characteristics of Sk 1248 are the same as its predecessors; the combined electrical-hydraulic control system is retained. Similarly, the use of two steam generators is retained, one operating in the cruising range and the second being turned on when the throttle is set for full thrust. The drawing also contains a number of penciled comments in German, indicating that it was not satisfactory. Indeed, the arrangement as stated would permit the system to start irrespective of the position of the pilot's control. This result is, of course, undesirable.

The detail design of the H_2O_2 regulator (22) is not felicitous, since the possibility of leakage cannot be ruled out and, hence, the second steam generator may be expected to start without warning.

While the design proposed in the present arrangement appears to be a definite improvement over its predecessors, it can hardly be said to be satisfactory, because of the retention of the electrical starting system and the parallel steam generators.

Version No. 8 ERK 12274, dated March 1944 (See Fig. 11)

This arrangement was prepared by the Zuhlsdorf division and suggests an approach completely different from any of the previous units. The most important single difference arises out of the elimination of all electrical controls and the substitution of a hydraulic system using H_2O_2 as the working fluid. The kinship between this aspect of the system and that in Version No. 4 should be noted.

Other changes were:

1. The electric motor start was abandoned and a Walter type gravity starter (FA and GE 1) was substituted.

2. A hydraulic distributing control (A) was introduced for both timing and throttling.

3. A pressure balancing valve (B) was suggested to permit the matching of the respective pressures of the H_2O_2, the acid, and the Tonka.

4. The acid and the H_2O_2 pumps were geared to the turbine, while the Tonka pump was driven directly. The entire suggestion is reminiscent of BMW activity on the P 3390A.

Version No. 9 Sk 1297, dated April 1944 (See Fig. 12)

This arrangement resumed the line of thought presented in Versions 1 through 7. It represents the furthest extent to which the design analysis was carried, after which point it was frozen. Components were fabricated and tested between August 1944 and February 1945.

Sk 1297 was important as providing the basis for the production unit 109-708B. It retains the major features which have characterized the main line of this development, with the exception of simplifying changes in the regulator and in the valve arrangement. The salient features, including the system of overriding clutches, electric start, and dual steam generators, are retained.

A new thrust range was selected, based on further studies for Me-163 performance. It resulted in a new throttling requirement which set up the following thrust requirements:

Cruise Chamber	3300-1320 lb
Climb Chamber	1100-4400 lb.

The requirement for continuous thrust variation was retained, representing a reversal from the earlier requirements. 12/

The outstanding feature of this version pertinent to the present report is that it has a throttled control. Since it merits detailed description, attention is directed to that portion of Fig. 12 enclosed in the heavy line and comprising the regulator and its valves.

The cruising chamber control is composed of an on-off valve (22), a regulator section (34), and its associated pressure switch (37). The climb chamber is actuated by on-off valve (25) and regulator portion (35).

The object of the regulator is to control the T-stoff supply to the turbine, and hence the pump power determining the pump output. The regulator was also designed to compensate the turbine for deviations in the steam generator output and turbine performance. Hunting is prevented by the arrangement of the control, which lags the turbine output behind the pump, thereby damping the system.

Regulator Construction

Since only layouts of the regulator of the P 3390C are available, the construction as shown on the drawing D-5-3390C-7 (Fig. 13) will be analyzed. Basically, the regulator assembly consists of three controls: a cutoff valve (1) for the T-stoff delivery port to the cruise-chamber steam generator, a slide valve (2) to meter the propellant to the first generator, and a similar valve (3) to control the input to the second generator.

Movement of the throttle is transmitted through a linkage to a gear segment. This, in turn, rotates a gear keyed to a shaft which has three cams (4, 5, and 6) keyed to it. The cams are located directly below the valves, and are so designed and arranged relative to each other that the sequence of operation is coordinated with the motion of the pilot's throttle.

The cutoff valve consists of a 0.197 in. diam steel rod located at right angles to the 0.236 in. diam drilled outlet hole from the regulator that controls the steam generator (for the cruise chamber operating range). In its upper position, this rod almost blocks the outlet passage, while in its lower position it does not interfere with the passage of T stoff. The steel cam is a simple, two-position design which closes the valve for 110° motion of the shaft (approximately 40° motion of the pilot's lever) and allows it to remain open for the remaining 250° shaft rotation. Vertical motion of the cam is transmitted directly to the shaft through a roller pinned to a "U" bracket on a piston. The steel piston slides in a reamed hole in the aluminum alloy housing, and bears directly against the lower end of the valve shaft. Leakage of T stoff past the valve to the atmosphere is prevented by a flexible, stainless steel bellows (7), which is welded to the double concentric washers and held in the housing against a sealing gasket by a hollow nut. A similar washer bears against a shoulder on the shaft and is held in place by a standard hex nut. Leakage is prevented by means of a thick, synthetic gasket or washer between the nut and the washer. Proper tightening of the nut squeezes the gasket into the shaft threads. This effectively seals and also provides a means of locking the nut to the shaft.

12/ The logic of the earlier conclusion would appear to be better substantiated in the light of Me-163 operational tactics. Mach-number limitations would appear to preclude full- or even-throttled thrust of the climb chamber at altitude.

The two H_2O_2 metering pistons (8 and 9) are identical in size and shape. They are hollow steel cylinders 3.7 in. long and 1.0 in. maximum diam, with a diaphragm or web in the center, to which a shaft is attached. The pistons are necked down to about 0.8 in. in diam for a space 1.1 in. long in the center and 0.7 in. down from either end. The pistons slide in steel bushings (10 and 11) which are pressed into the housing and are reamed and lapped on the assembly. Properly drilled holes in the sleeve connect annular grooves in the housing around the sleeve to the necked down portion of the piston and from there to the outlet fitting leading to the steam generators.

The 0.15 in. diam bolt in each piston serves as a clamp to hold on either side of the central web one washer each of two stainless steel bellows (12, 13, 14, and 15), constructed similarly to that explained for the shut-off valve. The outer ends of the bellows are attached to 1.3 in. diam washers which are held in the housing by hollow, spanner-type nuts. Sealing of the inner space is achieved by AN-902-type synthetic gaskets clamped between the washers and the housing. A washer-face nut is tightened down against a tubular spacer around the shaft. The inner end of the spacer bears against the the central washer of one of the bellows assembly and the inner head of the bolt against the other. Thus, tightening of the nut clamps the two washers together against hubs on the central web of the piston. Gaskets between the washers and the hubs prevent leakage.

Both faces of the washer nut act as seats for springs. One set of springs (16 and 17) is placed between the inner face of the nut and the outer face of the lower bellows washer. The other set (18 and 19) is placed between the outer face of the nut and the inside of a cup-shaped piston which carries the cam follower on a "U" clamp, as previously explained. The steel pistons for both regulators slide in reamed holes through the center of the special nuts (20 and 21) which retain the lower bellows assembly washers.

The steel cams are machined and then hardened and ground to final shape. Positive motion of the cams, as well as their locations relative to each other, is assured by proper location of the key ways. The possibility of misassembly is prevented by means of hubs on only one side of the cams and by the use of spacer tubes of varying length between them.

The regulator housing is machined from a block of aluminum approximately 8 x 5 x 4 in. The valve cavities are drilled, bored, and reamed to shape, and connecting passageways are drilled to suit. The cam portion of the block is milled away, except for a wall on either end to support the cam shaft. A sheet-metal cover encloses this portion and prevents the entry of dirt. The exit and entrance fittings are of the standard, flared-tube-connection type, sealed with AN-902-type gaskets. All blind holes are plugged with hex-head cap screws and sealed by gaskets under the head of the bolt. The assembly weighs approximately 6 to 8 lb complete.

Regulator Operation

The T-stoff propellant regulator is connected by means of gears, levers, and linkage to the pilot's throttle lever. The total movement of the throttle is approximately 110° from the zero to the full thrust position. This is transformed by gearing to 330° rotation of the cam shaft. The arrangement is such that approximately the first 40° motion of the throttle controls the thrust of the small chamber from "off" to 1320 lb. The next 30° movement causes the thrust of the cruising motor to drop back to 330 lb, switches on the large chamber, and increases the combined thrust to 1430 lb. The last 40° of throttle movement so regulates the turbine-pump output that the thrust of the two chambers rises from 1430 lb to 5500 lb.

After the start button has been pressed (Fig. 12), the starter motor rotates the T-stoff pump and sends the peroxide under pressure to the servo-operated on-off valves (22 and 25) leading to the regulators. Movement of the throttle makes an electrical contact (36), which activates the solenoid pilot valve of the first on-off servo. This servo valve is then forced open by T-stoff pressure acting against a piston, and the T stoff flows into the first regulator. It then flows through drilled passageways into the upper and lower annuli surrounding the balancing piston and sleeve. The upper and lower holes in the sleeve permit the propellant to impinge on both ends of the semi-floating piston and thus balance any unequal end thrust.

Reverting to Fig. 13, the position of the piston in the sleeve is determined by the cam position, and hence the throttle setting. Rotation of the cam forces the cam follower and the piston upward. This movement is transmitted through the spring to the washer face nut, and thence through the connecting shaft and sleeve to the balancing piston. Upward movement of this piston partially uncovers the 0.039 x 0.473 in. slit port (22) in the sleeve just above center. T stoff then flows from the upper annulus, through the central necked, down portion of the piston, and back out through the central hole in the sleeve. From here it is piped to the first steam generator.

Steam generated by the catalytic action of the permanganate stones on the peroxide enters the turbine. As it builds up speed, the pumps deliver their rated output, and the starter motor cuts out. Further rotation of the cam by the pilot's throttle may then uncover more of the slit area, allowing more T stoff to flow to the steam generator, until the thrust of the cruising chamber increases to the maximum value of 1320 lb. Any sudden surge of T stoff from the pump is transmitted by momentum to the balance piston. This produces a momentary partial closing of the inlet slits, and thus tends to reduce the turbine-pump speed until equilibrium is again reached. The reverse takes place if there is a sudden drop in pump pressure. It is extremely important that the actuating springs be accurately designed, manufactured, and calibrated in order properly to balance out the momentum forces. However, the small springs and the dashpot effect of the T stoff on both sides of the balance piston prevent rapid fluctation of the outlet flow. This lag in reacting to changes in pump output tends to stabilize the entire system.

The regulator performance is determined by the lifts of the respective regulator cylinders. These, in turn, are determined by the cam motion. Figure 14 was developed from an analysis of Fig. 13 and displays the valve lift as a function of cam rotation. It will be noted that as the cam shaft is rotated the cruising valve gradually lifts to a maximum. Before the climb chamber may be turned on, the cruising valve lift is dropped, thereby throttling the steam generator and, hence, reducing the turbine speed. This arrangement has the effect of dropping the cruising chamber thrust, and permits both climb chamber and cruise chamber to build up from very low values.

The relevant regulator performance parameters are presented in Fig. 15 for both the cruising chamber regulating cylinder and the climb chamber regulating cylinder. In evaluating the over-all T-stoff supply to the steam generator as a function of thrust, it is necessary to add both values in the region above 1430 lb thrust.

The overlapping of the respective sections may be viewed in the light of the cam development shown in Fig. 14. An interesting feature of the design is the use of the shutoff valve to restrict the T-stoff flow to the steam generator. This would appear to indicate that the use of the pistons by themselves is not satisfactory.

Certain mechanical details may also be noted. The movement of the cams beyond the maximum total thrust position is prevented by a throttling lever stop. If the rotation continued beyond the stop, the cam follower would drop off the cam and the throttle could then not be returned to zero. It may be concluded that the over-all performance of the regulator is dependent on the precise balances of the spring forces and the accurate determination of the areas involved. This type of regulation requires extremely accurate manufacture, and may be expected to cause high rejection rates. The need for balancing spring forces is a particularly difficult point.

Effect of Regulator on Engine Performance

It will be recalled that the P 3390C throttling control consists of varying the pump speed. This, in turn, is achieved by controlling the flow of H_2O_2 to the steam generator by the regulator valve, whose operation and performance was discussed above.

Figure 16 gives the steam generator performance as a function of thrust. It may be correlated with the regulator performance by using it in accordance with the above discussion. Fig. 17 gives the turbine-pump performance corresponding to the steam generator output at the respective thrust levels.

The power output of the turbine is proportional to the steam pressure and to the quantity of steam. If the pressures at any two points are equal, then the horsepower is a direct function of the steam flow. This is exemplified by reference to Figs. 16 and 17. For thrust values of 1320 lb and 5720 lb the steam pressures are equal at 340 psi, and the steam flow values are 0.446 lb/sec and 1.064 lb/sec, respectively. The turbine speeds are equal to 30,000 rpm at both points. This may readily be checked by the following identity:

$$\frac{HP_{1320}}{HP_{5720}} \cong \frac{(PQ)_{1320}}{(PQ)_{5720}}$$

$$\frac{111.2}{266} \cong \frac{340.6\ (0.446)}{340.6\ (1.064)}$$

$$0.418 \cong 0.419$$

The use of two steam generators introduces an additional difficulty in the requirement that each be matched to generate equal pressures at the same throttle setting. Experience with catalyst stone steam generators indicates that this is rather hard to do, in view of the possibility of different pressure drops and injector performance from unit to unit. BMW apparently realized this difficulty because the final version of the sequence, the 109-708, eliminated the second steam generator. While tests were never conducted to substantiate this fact, it is safe to conclude that the use of a single steam generator would prove to be more satisfactory than that proposed here.

Figure 18 presents the sea-level engine performance parameters as a function of thrust. The specific propellant consumption for the cruise motor alone varies from 7.1 lb/1000 lb sec impulse at 330 lb thrust to 5.37 at 1320 lb thrust. It then increases to 7.10 again at 1430 lb thrust, because both the small and large motors are operating at their lower throttling range extreme. The w_{sp} decreases again to 5.37 at 5720 lb thrust. The reason for the variations in w_{sp} with thrust has been explained in a previous section.

It is interesting to note that, although the specific propellant consumption curve for the motor and steam generator combined is practically parallel to that of the motor, it diverges slightly with an increase in thrust. This is true for both the small thrust and the combined thrusts. The reason for this deviation is apparent upon examination of the turbine efficiency curve from Fig. 17. The efficiency varies directly as the thrust from 330 lb thrust to 800 lb, and from 1430 lb to 3400 lb, and thereafter deviates downward with a further increase in thrust. Obviously the decrease in turbine efficiency results in a greater steam consumption for any given power output. This is directly reflected in the over-all specific propellant consumption.

Figure 19 plots specific propellant consumption as a function of the throttling range for various altitudes. Attention is called to the fact that the propellant consumptions do not match those of Fig. 18. This is apparently true because both sets of calculations are based on theory, making use of differing sets of prototype test data. Decision as to which of the two curves is more reliable is made more difficult by the fact that both curves were drawn in early 1944, within approximately a month of each other. The general adverse effect of throttling on engine performance is, however, illustrated by both curves. While 20% throttling does not appear to have a particularly adverse effect on efficiency, further increases result in a progressive deterioration. These may be accounted for in part by the shape of the nozzle coefficient curve in the working range of chamber pressures, and also by worsening injector performance.

The importance of the nozzle coefficient is further illustrated by the spectacular improvements predicted for operation at increased altitudes. The predicted improvement is quite spectacular. For example, w_{sp} at full thrust equals 5.1 lb/1000 lb sec impulse at sea level, and decreases to 4.6 for the same thrust at 52,500 ft.

The deterioration of performance with throttling is quoted as being much less at altitude than at sea level. This would appear to indicate that the throttling curves presented are based largely on varying the nozzle coefficient with altitude. Thus, for 80% throttling, the sea level consumption increases by 34.3%, while for 52,000 ft by only 17.4%.

Version No. 10 109-708B, Sk 1329, February 1945

The BMW 109-708B represents, for practical purposes, the final stage of the P 3390C development. (See Fig. 20. Version No. 11 embodied only minor changes.) After spending approximately a year on the P 3390C Version No. 9, including component testing, it was decided that the urgency of the situation was such as to require that a production article be made available without delay. Accordingly, the Version No. 10 design was most drastically simplified by replacing the H_2O_2 pumping system with a Walter pressure-fed steam generation system. Similarly, two BMW steam generators were eliminated, and a single Walter catalyst stone type substituted. This change made possible a corresponding simplification of the regulator control from a set of metering pistons to a needle-valve arrangement.

The method of control, however, remained the same. Throttling was achieved by pure speed control, but the throttling range is now discontinuous. The cruising chamber may be throttled from 1100 lb to 330 lb, and the climb chamber from 4400 lb to 2970 lb. There is no possibility of throttling the engine between 1100 lb and 3730 lb.

A further change influencing the control system arose from the use of compressed gas to supply the T stoff to the steam generator. This eliminates the difficulties consequent on variations of the T-stoff output pressure during throttling, and also makes hunting impossible. The T-stoff regulator is now a variable orifice control instead of a combined variable orifice + speed control, as in the previous versions.

Regulator Structure and Operation

While no drawings or detail descriptions of the T-stoff throttle valve were located, enough information has been deduced from calculated curves to permit a reconstruction of the regulator operation principle. It appears that the regulator consisted of a simple needle valve, whose conical poppet may be accurately positioned with reference to the seat. Poppet motion is linked to the pilot's throttle and to a solenoid turbine overspeed safety which may override the pilot's control.

Reference should now be had to Fig. 21, giving regulator performance; Fig. 22, corresponding steam generator performance; Fig. 23, turbine-pump performance; and Fig. 24, combustion chamber performance.

In its closed position the steam generator throttle acts as the shutoff valve for the T stoff. As soon as the pilot's throttle is set to the start position (330 lb thrust), the conical plug is moved so that it partially unblocks the orifice and allows 0.177 lb/sec of T stoff to flow to the steam generator. The 58 psi pressure generated in the steam generator develops 14.4 hp output from the turbine at 8050 rpm. The pumps then deliver 2.34 lb of propellant per sec at 188 psi to the small combustion chamber.. A thrust of 330 lb at a chamber pressure of 102 psi is then developed.

Further movement of the pilot's lever gradually opens the throttle orifice area from 0.00184 sq in. to 0.00874 sq in. The thrust of the small chamber increases to 1100 lb, and the pumps reach their maximum speed of 17,000 rpm. The pressure drop across the regulator has decreased from 510 psi at the start to 314 psi, and the T-stoff flow has risen to 0.665 lb/sec. This setting corresponds to the maximum thrust from the cruise chamber.

When the pilot's throttle is moved beyond this setting, an electrical contact is closed and the shutoff valves of the large combustion chamber are opened automatically. Because of this increased demand on the pumps, caused by the sudden increase in discharge area, the speed momentarily drops and the pressures decrease. The throttle setting is not changed during this transition period and the turbine-pump speed increases fairly rapidly to 13,280 rpm. The pump output is now 21.4 lb/sec at 524 psi, and the combined thrusts equal 3740 lb. The turbine efficiency drops because of this change and the horsepower output decreases from 133.8 at 1100 lb thrust to 114 at 3740 lb thrust. Both cruise and climb chambers are now working at relatively low chamber pressure.

The total thrust may be gradually increased to 5500 lb by opening the throttle orifice to 0.0276 sq in. The conical plug is completely freed from the 3/16-in. diam hole, and the T-stoff flow is 1.09 lb/sec. The turbine output is 240 hp at 17,000 rpm and the pump discharge pressure is 852 psi. The pressure in both chambers again reaches 341 psi. Throttling is done in the reverse manner to that above.

Figure 21 shows the regulator performance as a function of thrust. Since the regulator is nothing more than a variable orifice, the hydraulic parameters adhere approximately to the flow formula, $Q = CA\sqrt{\frac{2g\,\Delta P}{\rho}}$.

For example:

for 330 lb thrust

Q = flow through regulator = 3.67 cu in./sec
A = orifice area = 0.00184 sq in.
ΔP = pressure drop across regulator = 510 psi

for 1100 lb thrust

Q = 13.65 cu in./sec
A = 0.00874 sq in.
ΔP = 314 psi

$$\frac{Q_1}{Q_2} = \frac{A_1\sqrt{\Delta P_1}}{A_2\sqrt{\Delta P_2}}$$

$$\frac{3.67}{13.65} = \frac{0.00184}{0.00874}\sqrt{\frac{510}{314}}$$

$$0.269 = 0.269$$

If the flow formula presented above is rearranged and solved for the flow coefficient C, we have for 330 lb thrust:

$$C = \frac{Q}{A\sqrt{2g \quad \Delta P/\rho}}$$

$$= \frac{3.67}{0.00184\sqrt{2x32.2x(12)x510/0.05}}$$

$$= 0.713$$

Check calculations were performed for other thrust values and indicate that the same flow coefficient was used throughout the entire range of regulator settings. This is incorrect, since the flow coefficient will vary with the poppet position. However, this assumption is reasonably acceptable in a preliminary calculation, but it would have to be modified in accordance with test results.

Since the thrust is not variable between 1100 lb and 3740 lb, the curves on Figs. 21 through 24 are dotted in this region. Once the large chamber is cut in, the throttle is not moved until after the combined thrust reaches 3740 lb. As a result, the regulator performance remains constant and the curves are all horizontal.

Figure 22 is a plot of the steam flow from the generator and its pressure as a function of thrust. As the steam generator performance is directly dependent upon the amount of T stoff delivered to it through the regulator, the steam flow, W_t, is a direct function of the T-stoff flow, Q (from Fig. 21). Superimposition of the two curves substantiates this.

Figure 23 presents the parameters of turbine performance and their variations with thrust. The turbine speed, efficiency, and horsepower output, together with the pump-output pressures, are plotted to indicate their general trends. The values are conventional in the regions of controlled thrust and need no special explanation. The transition between 1100 lb and 3740 lb thrust is drawn as a straight line, but the performance does not necessarily follow this trend. The control is discontinuous in this range and the shapes of the curves are immaterial. When the large motor valves are opened, the pump-output demand changes the pump and turbine performance to such an extent that a new equilibrium is established at a lower speed but at a higher pump discharge. As was pointed out from Figs. 21 and 22, the steam generator performance remains constant throughout this transition period, but the turbine efficiency drops from 57% at 1100 lb thrust to 48.1% at 3740 lb thrust. This decreases the power output of the turbine from 134 hp to 114 hp. The turbine-pump combination theoretically stabilizes at 13,280 rpm, with a resulting pump discharge pressure of 524 psi. To maintain a uniform increase in horsepower output, the steam flow rate from the steam generator must increase in the regions of higher thrusts (Fig. 22) to compensate for the lower rate of increase of turbine efficiency for the same region. (See Fig. 23.)

Figure 24 shows the results of this turbine speed control on the engine performance. The specific propellant consumption of the motor with and without the T stoff required by the turbine and the chamber pressure are plotted against thrust. The curves in the transition period are again plotted as straight lines for convenience.

The specific propellant consumption of the cruising chamber increases from 5.2 at full thrust to 7.1 at 70% throttling. The specific propellant consumption for the higher thrust regions is quite comparable. It varies from 5.1 to 5.7 for 32% throttling from the maximum of 5500 lb thrust. For the same throttling of the cruise chamber, the specific propellant consumption rises from 5.2

to 5.85. The total specific propellant consumption of the system, including the steam generator, is also plotted. The shapes of the curves indicate that the corresponding pump and turbine efficiencies are taken into account in computing the T-stoff consumption.

Throttling of the A-4

The inclusion of the A-4 power plant in the discussion of throttling is of definite interest, although the total duration of throttled operation is very small (of the order of 3 sec out of 60 sec). This discussion will concentrate on the reasons for the control of thrust and the mechanism by which it is achieved. Because the total throttled duration is so short, no attempts were made to determine any changes in specific propellant consumption.

The requirement for throttled operation arose from the roughly elliptical flight path of the A-4 missile. The range is determined to a large degree by the missile velocity at the end of thrust according to the formula:

$$S = v_o^2 \frac{\sin 2\varepsilon}{g}$$

where S = range after combustion cutoff
v_o = velocity at cutoff
ε = angle of departure at cutoff.

Since the A-4 had a fixed climbing program, the angle, ε, remained constant after 48 sec of flight, and the range was proportional to the square of the velocity at combustion cutoff. This is shown by Fig. 25.

Figure 26 shows the flight trajectories for three different cutoff points. It will be seen that the accurate determination of the cutoff velocity is therefore essential, and that time delays must be minimized if accuracy is to be maintained.

Three practical methods of initiating this cutoff process were used:

1. Propellant Exhaustion

This method is obviously the least accurate, and is made the more difficult by oxygen evaporation. To facilitate control and minimize time lags, it was decided to shut the engine down by first reducing the thrust to 17,000 lb and then shutting off completely. It was found desirable to initiate the throttling process at a velocity of about 5% less than the final desired value. The throttling is achieved by pure pump speed control, in which the supply of T stoff to the steam generator is decreased before finally cutting it off completely.

2. Integration of Acceleration

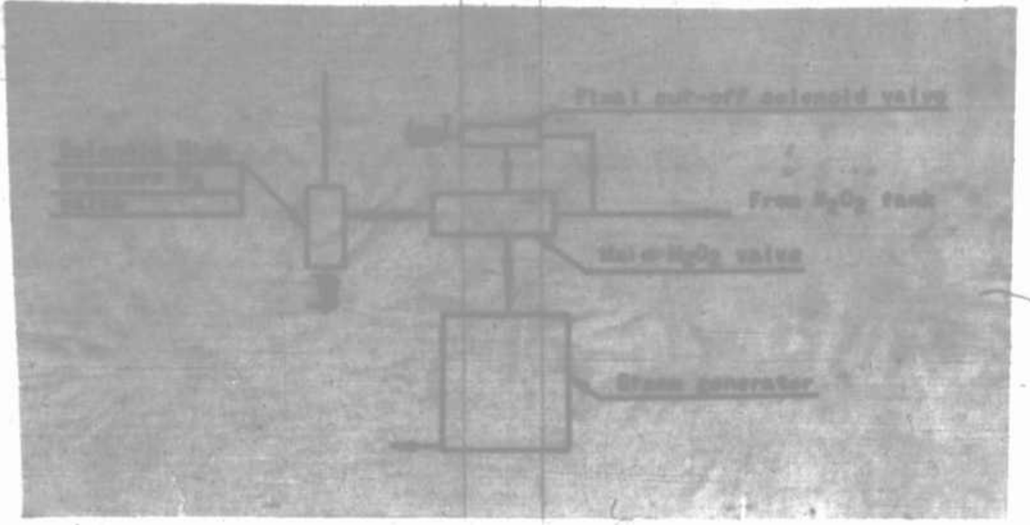
The velocity was measured by an accelerometer of the electric cell or gyroscopic type, and integrated with respect to time. The combustion cutoff process was initiated at a preset velocity. This method was used in about 50% of the test flights and in about 90% of the rockets sent against England.

3. Cutoff Signal Transmitted by Radio

The velocity was measured by elaborate signal receiving and transmitting sets using the Doppler effect. The cutoff signal was transmitted by radio at the correct velocity. This was used in about half the test flights, but for only about 10% of the flights to England, because of insufficient ground installations and increased danger of air attack during operation. However, it was more accurate than other methods.

More complete descriptions of these cutoff-initiating devices are given in other references.[13] The details are beyond the scope of this report.

Once the cutoff signal has been received, it is first transmitted electrically through relays to a solenoid valve. This valve opens and permits high-pressure gas to close the main, pneumatically actuated, H_2O_2 valve located just before the steam generator. The final signal is also transmitted electrically to another solenoid valve located in a line which leads from the peroxide inlet side of the main valve, and by-passes this valve. Schematically, the setup is as shown in the sketch below:



The main peroxide cutoff valve is shown on Fig. 27. It is composed of a cast aluminum alloy housing with synthetic rubber cup seals, a steel piston (2), a steel spring (4), and a steel poppet (3). The peroxide enters through port (6) and leaves via port (7). The final or by-pass peroxide cutoff valve is located in a line between the inlet and port (8), so that the position of the poppet (3) either closed or open does not influence the flow of peroxide through the smaller valve. By the action of spring (4), the poppet (3) is normally held closed against a synthetic washer inserted in the casting. High pressure gas entering the valve cover through port (1) forces piston (2) downward against the force of the spring (4). This motion is stopped by the skirt of the piston striking against shoulder (5) on the housing. Leakage of gas past the piston is prevented by the upper cup seal and the space under the piston is vented to the atmosphere through hole (9). Leakage of peroxide past the stem is prevented by the lower cup seal. Both seals are held in place by steel washers and snap rings.

The poppet is screwed into the piston, but no provision is made for locking it in place. This is a defect in detail design. The valve cover and the inlet fitting are screwed into the body and sealed by metal-to-metal fits. The cover and fitting are lock-wired together to prevent inadvertent loosening.

13/ APJ Document 5-5 and FE 125.

The final cutoff valve is shown in Fig. 28. It is composed of a standard solenoid having a movable core (8) which is attached to a long narrow push rod (9). This rod extends through a small central hole (10) in a large piston (4) and pushes against a smaller piston (2). Both pistons are normally held closed against soft seat inserts, (5) and (3) respectively, by the upward force of spring (1). Peroxide enters port (6) and leaks around the periphery of the loosely fitting piston (4). The pressure of this peroxide reacting against the under sides of both pistons further holds them closed until the valve is actuated.

When the final cutoff signal is received, the solenoid is energized. The core and stem move downward, and the small piston (2) is forced away from its seal (3). This permits peroxide to flow through the orifice (10) faster than it can leak in from the inlet. This relieves the pressure from the under side of the large piston and allows the skirt of the smaller one to engage the snap ring (11) and force the piston (4) open. Peroxide can then flow from the inlet (6) through outlet (12) into the central body of the previously described valve and then into the steam generator. Leakage past the stem (9) into the solenoid housing is prevented by a cup seal held in place by a washer and snap ring. Screwed exterior fitting and covers are prevented from loosening by lock wire.

The valve and the connecting lines are of sufficiently small size that the peroxide flow is limited to a value which cuts the thrust to the prescribed 17,000 lb. When the valve is de-energized the spring forces the pistons closed in reverse order and all peroxide flow ceases. The turbine stops and the thrust drops to zero in about $2\frac{1}{2}$ sec.

This four-to-one decrease in thrust increases the specific propellant consumption, but as the low stage thrust is in operation for only a few seconds, this is immaterial to the operation and the resulting range of the missile.

Propellant Throttling and Speed Control

The general characteristics of propellant throttling have been described above. It offers an extremely simple method of control but, unfortunately, has adverse effects on the propellant (by warming it) and also wastes the energy lost in the throttling process. It is, therefore, reasonable that pure propellant throttling was never encountered but rather was found in combination with pump speed control. It is also noteworthy that the HWK 109-509 rocket engine, which was one of the most successful developments, made use of this method.

Inasmuch as the throttling and pump control are closely related with the over-all design of the engine, it is desirable to begin an analysis of the 109-509 throttling by a general description of the engine operation.

Operation of the HWK 109-509

The operation of the 109-509A-2 rocket engine may be followed by referring to the piping layout schematic, APJ Dwg. No. 051-900-14-00. (See Fig. 29.) The main propellant tanks (18 and 19) are first filled with fuel (hydrazine hydrate + methyl alcohol) and oxidizer (hydrogen peroxide), and the small gravity feed tank (29) is filled with H_2O_2. When the tank valves (20 and 21) are opened, propellants flow from the tanks through the statically sealed pumps (13 and 15), through lines (3 and 2), to the regulating valve (25). H_2O_2 also flows from line (2) through line (17) to the pressure regulator (27).

Operation is started by opening the hand valve (31) of the gravity tank (29) and allowing the peroxide to flow into the steam generator (23). Steam, formed by the action of H_2O_2 with the catalyst in the steam generator, flows through line (1) to the turbine (14), starts the turbine rotating, and discharges to the atmosphere through the exhaust line (30). Steam also flows through line (42) and check valve (28) to the gravity tank by way of line (41), thereby maintaining practically a constant head of H_2O_2 to feed the steam generator during idling operation.

Steam also flows from line (1) through line (16) to the heat exchanger (26), and discharges into the combustion chamber through line (43). Ejector pumps (not shown) operated by steam from line (1), create a suction in the discharge section of each pump (now rotating with the turbine), and expel all the trapped air in lines (2) and (3). Lines (2) and (3) are now full and partially pressurized. The excess propellants return from the pumps to their respective tanks through lines (22) and (24).

The hand valve (31) can now be turned off; H_2O_2 is fed to the steam generator (23) from the idling portion of the throttle valve (27) via line (40), check valve (28), and line (42). The gravity tank (29) is refilled for the next start from line (41) through the check valve (28).

The rocket engine is now ready to start. The throttle lever in the cockpit is turned to No. 1 position. This lever is mechanically connected (line 44) to the control portion of the propellant regulator (25) and to the H_2O_2 throttle valve (27). When moved to the first position, it allows fuel to flow from the regulator to the cooling jacket of the combustion chamber through line (4), back to the regulator through line (5), and then back to the first stage injector (33) through line (6) and the heat exchanger (26). H_2O_2 at the same time flows from the regulator (25) through line (9), through the first stage injector (33), into the combustion chamber (32), igniting with the fuel and producing 330 lb of thrust. The movement of the throttle simultaneously permits more H_2O_2 to flow to the steam generator (23), speeds up the turbine-driven pumps, and maintains the propellant flow and pressure at the proper values.

Further extension of the pilot's throttle lever allows propellants also to flow through lines (7) and (10), and (8) and (11), to the second- and third-stage injectors (34) and (35), respectively, thereby producing an ever-increasing thrust to the maximum value of 3740 lb. The unit may be throttled back at will to any desired thrust value, including complete shutoff, by controlling the respective regulators. A lever controlling valve (31) is accessible to the pilot, who may restart the engine at any time by following the previously described starting procedure.

A constant mixture ratio is maintained at all times by the regulating valve (25), and the speed of the pumps is controlled by means of the pressure regulator (27). These valves will be explained below in detail.

Regulator Structure and Operation

The foregoing description has emphasized the central importance of the regulator valve and of the turbine regulator (parts 25 and 27, respectively, in Fig. 29). The proper coordination of these controls permits a precise regulation of the engine through the entire throttling range. It also acts as mixture ratio and shutoff valve control, and performs various other auxiliary functions. It is, therefore, desirable to consider the regulator and turbine throttle in detail.

The following discussion is concerned with the construction and operation of the main regulator. Figures 32 through 35 show the valve assembly and components in relation to each other. The regulator may be divided into four main sections.

a. Propellant cutoff valves
b. Propellant-metering control
c. Pressure ratio balance pistons
d. C-stoff filter

Reference should be made to Fig. 30, which is the basis of the following detail analysis. This will be facilitated by first defining the various propellant inlets and outlets shown in the figure.

I. C-stoff main inlet from pump
II. C-stoff outlet to motor cooling jacket
III. C-stoff inlet from motor cooling jacket
IV. C-stoff outlet to motor - Stage I
V. C-stoff outlet to motor - Stage II
VI. C-stoff outlet to motor - Stage III
VII. C-stoff blowout connection
VIII. T-stoff (peroxide) outlet to motor - Stage I
IX. T-stoff (peroxide) outlet to motor - Stage II
X. T-stoff (peroxide) outlet to motor - Stage III
XI. T-stoff drain (cutoff valve)
XII. T-stoff drain (common)
XIII. C-stoff drain (common)
XIV. C-stoff drain (cutoff valve)
XV. T-stoff main inlet from pump
XVI. C-stoff servo line to motor drain valve
XVII. T-stoff blowout connection

Throttling and shutoff are achieved by the rotation of the metering valve (11) by the pilot's throttle lever through linkage (144). Rotation of this valve meters the servo fluid, C stoff, through the proper channels, and permits the pilot to have complete control over the entire thrust program. The operation is automatic once the servo control valve is moved to the proper position.

The regulator assembly is bolted to the engine mount plate by means of hex-head cap screws. These screw into steel inserts similar to the one-piece Rosan type familiar in this country. The inserts are screwed into cast bosses on the housing, and are held in place by a slight interference fit. The bosses are on two separate valve castings, and are faced flat after assembly to insure flush mounting. This is done to prevent misalignment of internal moving parts and consequent jamming. It also prevents cracking of the castings during assembly. The cap screws are prevented from loosening by lock wires.

The regulator housing consists of four separate aluminum alloy castings, in addition to four cast covers. (See Fig. 33.) The valve is separated into a T-stoff side, a C-stoff side, a spacer piece, and a C-stoff filter housing. Covers are mounted on each end of the cutoff valve assembly; one cover seals and retains the rotary metering control, and another caps the filter housing.

Accurate machining of these castings is required to insure proper alignment and sealing between each section, but the use of bushings and the sectional connecting push rods permits reasonable assembly tolerances.

The liberal use of synthetic rubber seals and properly located drain ports, together with the sectional design, practically eliminates the possibility of propellant intermixture. Coincidental failure of two opposed seals might permit propellant mixing, but the likelihood of such a happening is most remote.

Aluminum-alloy castings are anodized and impregnated with wax after machining to prevent corrosion. All pistons except the aluminum servo piston (10) are made of hardened steel, as are all push rods and similar moving parts. The bushings, cylinder liners, and valve seats are made of brass on the C-stoff side, and of steel wherever T stoff is present. This is because any copper present acts as a catalyst for the peroxide and causes its decomposition. All springs are of steel.

The regulator occupies a space approximately 11 x 11 x 15 in., and weighs 28 lb.

<u>Propellant Cutoff Valves</u> (See Fig. 30, parts 12 and 13)

This section may be divided into three parts: C-stoff shutoff valve (13), servo piston (10), and T-stoff shutoff valve (12). Both poppets have hardened steel conical seats. They are guided by pressed-in bushings, and seat on a hardened-steel insert shrunk into the aluminum housing. The bushing bore and the seating surface of the insert are machined after assembly to insure a good fit.

The aluminum servo piston (10) has a synthetic rubber cap seal (47) on the pressure side. This seal is held in place by a steel washer (25) fastened to the piston by flat-head screws (60). It prevents excessive leakage of C stoff past the piston. Any leakage is vented to the pump suction through the drain fitting (XIII). The piston is normally held closed by a steel spring (107).

The C-stoff valve is mechanically connected to the piston by means of a button-headed steel shaft (28) sliding in a brass bushing. The heads of this shaft slide into milled "T" slots on both the valve and the piston. The fit of the heads in the slots is quite loose to allow for the eccentricity of the bushings. The head bearing on the C-stoff valve is cylindrical to allow for any nonparallel shaft tolerances.

A cylindrical steel shaft (30), guided in bushings pressed into the spacer casting, transmits the piston movement to the T-stoff poppet valve (12). The motion is transmitted only by compression, since there is no connection between the shaft and the piston or the poppet valve. This arrangement permits assembly without maintaining excessive machining tolerances. It also allows the C-stoff valve to close even if the T-stoff valve should become stuck. A nominal 0.02 in. gap between the end of the intermediate shaft (30) and the T-stoff poppet shaft allows for assembly tolerances, and insures that the spring (33) keeps the poppet shut during the "off" and "idling" position.

Leakage of C stoff past the poppet stem (13) flows back to the pump inlet through the reducing nipple (143). Leakage around the threads of the nipple to the outside is prevented by an AN-902-type synthetic rubber gasket (78). Leakage of C stoff from the inlet port (1) into the servo piston chamber is prevented by means of a metal-re-enforced synthetic rubber washer (26), screwed to the housing and wiping the intermediate connecting shaft (28). As mentioned above, leakage past the piston (10) is limited by the cup seal (47). The small amount that does get by is carried away, through the common drain, back to the pump inlet through the fitting (XIII).

Propellant leakage around the push rod (30) into the intermediate casting space is prevented by the use of bellows-type synthetic rubber seals (46). These seals are so constructed that they tightly grip the grooves on the shaft and the housing. The tension in the rubber effectively seals the joints, and the bellows-type construction permits unrestricted movement fore and aft. These seals provide a practically fail-proof joint, are easy to assemble, and have an almost unlimited life.

Sealing of the T-stoff poppet stem and cover is similar to that of the C-stoff poppet. All T-stoff leakage is piped from the common drain through fitting (XII) to the turbine exhaust. Drainage of the T-stoff chamber before the valve may be done through fitting (XI).

The main cutoff valves (12 and 13) are closed during "off" and "idling" by the combined force of two springs (33 and 107) and of the propellant pressure acting on both conical seat valves. The valves are simultaneously opened by C stoff acting on the servo piston (10).

C stoff from the pump discharge enters the valve chamber through inlet (1) and is blocked by the valve. Simultaneously, T stoff from the pump enters the regulator through inlet (XV) and is similarly stopped. As soon as the control lever (144) of the metering cylinder (11) (explained below) is turned more than 13°, C stoff is led through drilled holes from inlet (1), through the cylinder (11), and through a restricting orifice (51) back to the servo piston (10). Pressure is slowly built up behind the piston (10), forcing it and the cutoff valves (12 and 13) open. At the same time a portion of the C stoff under pressure is led from the cylinder (11) through fitting (XVI) to the combustion chamber drain valve. This valve then closes.

Orifice (51) prevents the rapid build-up of pressure behind the servo piston (10), and hence slows the valve's opening. This permits the closing of the motor drain valve before the full flow of C stoff from outlet (11) can go through the motor cooling jacket to the drain valve. The C stoff is then forced from the cooling jacket back to the regulator. It enters through the inlet (111), passes through the filter into the center of the metering control cylinder. Orifice (51) also prevents rapid valve shutoff and eliminates the possibility of water hammer.

As soon as the servo piston opens the poppet valves, T stoff flows from the cavity above the valve into the cast recess surrounding the three pressure-balance piston sleeves. It is prevented from flowing to the chamber by the closed position of these pistons.

The first step of operation is now complete. The pumps and propellant pressure have reached the proper idling values. The pilot's throttle may now be moved to the first-stage thrust position.

The valves may be shut by rotating the cylinder (11) below the 13° point. This drains the servo cylinder in front of piston (10) by way of the orifice (51) into the drain below the piston. The springs (33 and 107) and propellant pressure force the valve tightly against their respective seats, thus stopping the flow of propellants to the motor.

Propellant Metering Control (See Figs. 30 and 34)

The metering control (11) is a partially hollow, hardened-steel cylinder. It has a shaft on one end, to which is splined and bolted the actuating lever (144). Three oblique longitudinal rows of three ports (spaced 120° apart) are milled in the hollow portion, and a series of grooves are milled in the solid portion nearest the shaft. (See Fig. 37.) The cylinder rotates in a brass sleeve which is pressed into the housing. This sleeve (Fig. 31) has six rows of three holes each, corresponding longitudinally to the holes and slots in the rotary cylinder. Their relationship is such as to give the proper propellant flow for each throttle setting.

The cast aluminum housing has six annular grooves in alignment with the ports in the brass sleeve. Each of the three larger grooves is connected to an outlet fitting (IV, V, and VI). While test data is not available on the respective pressure drops, they appear to be of the order of magnitude of 100 psi, and form the propellant-throttling feature. The use of the same regulator on various versions of the 109-509 was achieved by changing the orifices and providing a new thrust-calibration card.

A small bleed hole (not shown) connects the center of the rotary cylinder to the shaft end. This permits C-stoff pressure to act on both ends of the cylinder, reducing the end thrust on the valve. Leakage along the stem is prevented by a graphite-asbestos packing (50) held in place by the cover (20). Leakage through joints or around fittings is prevented by synthetic rubber gaskets (e.g., 38, 82, 99, 39, etc.).

Longitudinal location of the rotary cylinder in the sleeve is fixed by a shoulder on the cylinder. A recessed brass washer acts as a bearing in the cover (9). Rotary motion is indexed from a milled stop on the cylinder, which butts against a corresponding stop on the sleeve. (See Fig. 37, view 13b.)

The C-stoff filter housing bolts on the open end of the rotary valve housing. It forms the entry port for the C stoff, and also effectively seals the joint between the two castings. A 0.02 in. gap is nominally allowed between the end of the rotary cylinder and the filter housing to facilitate assembly and prevent binding of the cylinder.

The operation may be broken down into five distinct steps: off, idling, and three thrust stages. The transition between stages, however, is quite smooth, as explained below.

<u>Off</u>

When the pilot's throttle lever is set at zero position, the rotary valve is against its stop. The relationship of the rotary cylinder to the fixed sleeve may be seen from Fig. 36, view 32a. The white portion represents the sleeve ports, and the black portion the alignment of the slots in the cylinder with the ports. Alignment in the off position is shown in the left-hand figure (No. 1). The pressure cylinder of the main servo piston is vented to the drain from port (2) through port (3), and the shutoff valves are closed.

<u>Idling</u>

The port alignment for the first 13° of rotation of the control lever (144) remains the same as in the off position, as shown by No. 2 in Fig. 36. The only change in engine operation during this first rotation is the movement of the steam generator throttle to the idle position and the subsequent build-up of the turbine-pump rotation to idling speed.

<u>Thrust Stage I</u>

When cruising thrust is desired, the pilot slowly advances the throttle to the first thrust position. This rotates the metering cylinder (11) until the small slot is fully uncovered by port 6. (See Fig. 36, view 32a, stage 3.) Simultaneously, ports No. 1 and 2 are connected. C stoff then flows from the main entry port through sleeve port No. 1 and is by-passed through the milled slot in the rotary cylinder into the servo cylinder through port No. 2 and orifice No. 51. (See Fig. 30.)

The main valves are then opened, and C stoff flows to the motor jacket and back to the propellant regulator. C stoff enters through the filter and flows into the center of the metering cylinder. The circumferential slot permits the gradual entry of C stoff into the injector line and into the space above the propellant-pressure-balancing servo piston. This primes the lines and prevents shock loads resulting from sudden surges of liquid. It also stabilizes the ignition of the propellants and results in a gradual increase of thrust.

It may be noted from Fig. 36, view 32a, stage 3, that the first-stage thrust port is completely open, and that the circumferential slots of the other two stages are partially uncovered. The sketch shows only one set of sleeve ports, but it should be remembered that there are three rows such as shown in Fig. 31. The total available exit port area for the first stage of thrust is approximately 0.17 sq in. For the flow of 1.25 lb/sec of C stoff there is less than 5 psi drop across this metering port. An additional control orifice in the outlet fitting (IV) has an estimated pressure drop across it of about 100 psi. If 50 psi is assumed for the remaining pressure drops through lines, fittings, etc., there is still available an injection pressure of 90 to 100 psi. (The chamber pressure at 450 lb thrust equals 50 psi.) Below this value the combustion becomes unstable and thrust control is not possible.

<u>Thrust Stages II and III</u>

Further rotation of the valve (11) gradually uncovers ports No. 5 and 4. (See Fig. 36, view 32a, stages 4 and 5.) The holes in the sleeve are so designed that as the second and third stage ports are uncovered the first and second stages, respectively, remain open. At maximum thrust, all three are wide open.

The total open-slot area for the first thrust stage is 0.17 sq in. The second thrust stage slot adds 0.20 sq in., making a total area of 0.37 sq in. The third stage slot is considerably [illegible] than the other two because six injectors are fed from this port in place of the three from each of the others.

The C stoff is led from each port through the respective fittings (V and VI, Fig. 30) to the second- and third-stage injectors. Orifices are screwed into each fitting to properly meter the C stoff to the combustion chamber. Simultaneously the C stoff is led from the annuli to the top of the proper propellant balance servo pistons, (2 and 3, Fig. 30, upper left hand section).

Thrust may be decreased gradually by reverse rotation of the rotary cylinder through motion of the pilot's throttle lever. In order to take full advantage of the propellant-regulator design, it is necessary to move the throttle lever gradually, allowing at least 15 to 20 sec from ignition to full thrust. Rapid motion in either direction cuts the stages in or out too rapidly and may result in line failure due to sudden surges of liquid under pressure.

Pressure Ratio Balance Pistons (See Fig. 34)

As mentioned above, the C stoff is metered to the motor by means of the rotary control valve. The T stoff, however, is controlled by means of servo operated valves. These valves are actuated by the C stoff, and therefore the timing and pressure of T stoff is directly dependent upon the C stoff. The construction and operation of this portion of the propellant regulator are dealt with below.

As shown in the upper left hand section of Fig. 30, the pressure balance piston group is located adjacent to, and in the same plane as the main shutoff, on-off valves. Care was taken to insure the separation of propellants to avoid intermixing and resulting explosions and fires.

Servo Pistons

The C-stoff side (1) has three bored holes whose axes are parallel to that of the cutoff valves. Into each bore is pressed a machined brass tube with a locating shoulder on the top. Steel machined pistons (23 and 24) are fitted relatively loosely into these tubes and bear against interconnecting steel shafts (29), guided by pressed-in sleeves in the spacer housing (6). The loose fit is necessitated by the differential expansion of the brass sleeve and steel piston (approximately 0.001 - 0.002 in.) when in contact with the hot C stoff (approximately 300°F) coming from the cooling jacket of the combustion chamber. The cylinders are capped by threaded aluminum covers (138 and 139) and are sealed by synthetic rubber gaskets (76 and 24).

Each cover contains a steel pin (122) enclosed by a threaded fitting (137 and 101). The pin (122) and fitting (101) are used to hand-check the movement of the pistons in their sleeves. This is done by unscrewing the fitting, reversing it, and pushing on the pin. Fitting (137) has threads on the outside. When this is unscrewed, reversed, and screwed down tightly against the steel pin, the piston is blocked open and the T-stoff flow through each cylinder may be individually checked. Each cover has a boss on the cylinder side which limits the outward movement of the piston. The top of each of the three servo pistons is connected by drilled channels in the casting to the respective annuli of the metering cylinder. Leakage of C stoff past the pistons is collected in a common drain channel and led to the pump inlet through fitting (XIII).

Spacer Block

The spacer block (6) separates the T-stoff section (2) from the C-stoff section (1). It is bolted to the other two castings by means of studs (61) mounted in section (1) and held by hex nuts (68). The nuts are locked in place by means of split lock washer (72), similar to AN 935.

The thrust pins (29) are guided in bushings pressed into this housing and reamed to fit on assembly. Leakage of propellant from either side around the shaft is prevented by special flexible synthetic rubber (Buna) seals (108 and 117). These grip annular grooves on the shafts, and are wired to grooves in the spacer housing. The main housing joints are sealed by special gaskets (116 and 36).

Machined shoulders on the shafts (29) in the C-stoff side bottom against the bushing before the skirt of the servo pistons can strike the spacer housing. This prevents damaging or burring the piston, which would prevent or impede its movement. The center of the spacer casting (6) is hollow, and is vented to the atmosphere. This prevents mixing of propellants if a seal should fail.

T-Stoff Metering Pistons (See Figs. 30 and 35)

The casting (2 on Fig. 30) houses the T-stoff-metering pistons (21 and 22) as well as the main T-stoff cutoff valve (12). The outlet side of the valve is connected directly to a cavity approximately 1-5/16 in. wide, 3/4 in. deep, and 4-1/4 in. long. Three holes are bored through this casting. Their axes are perpendicular to the long axis of the cavity and pass through its center. Steel sleeves are pressed into these holes and jig-reamed on assembly to align longitudinally with the three servo pistons in the C-stoff side. Steel pistons (21 and 22) are inserted in the sleeves and lapped in place to insure proper alignment.

These pistons are hollow except for a 1/8 in. thick bulkhead at the spacer casting end. The thrust pins (29) bear against this bulkhead and transmit the C-stoff servo piston motion to the T-stoff pistons. A circumferential shoulder on the inside of the pistons acts as a seat for the springs (34 and 35). These bear against washers (132 and 133), which are retained by wire snap rings (42 and 43).

Each sleeve has two radial holes opening into the T-stoff supply duct. A similar pair of holes in the pistons permits passage of T stoff from the duct into the center of the piston. Each piston assembly is surmounted by a cylindrical chamber which is capped by covers (93 and 90). Each cover has short, hollow head bolts (105) which may be removed for inspection purposes. All screw joints are sealed by AN-902-type gaskets (76, 77, and 83). Outlets VI, IX, and X connect with lines to the T-stoff propellant injectors. Fittings VIII and IX are flared tube fittings, while outlet X is a flange connection to accommodate the larger pipe size required in third-thrust stage.

As the metering cylinder is rotated, the various thrust-stage ports are uncovered. C stoff simultaneously flows from the metering valve (11) to the respective injectors, and through by-pass holes in the casting to the top of each servo piston in chronological order. The C stoff, under pressure, acts as the servo fluid and forces the control pistons toward the T-stoff side. This motion is transmitted through the push rods to the T-stoff-metering pistons. As they move outward against the force of the springs, the radial holes in the piston come into alignment with those in the sleeves. T stoff is thus gradually admitted from the supply duct into the center of the pistons. It then flows into the collectors and through the lines to the proper T-stoff injectors.

As soon as T stoff is admitted into the center of the piston, it exerts a pressure opposing that of the C stoff. The C-stoff and T-stoff pistons have the same cross-sectional area, and therefore the propellants must exert equal and opposite pressures, maintaining a static pressure balance. If T-stoff pressure rises too high, it forces the entire assembly toward the C-stoff side. This restricts the inlet port area, increases the pressure drop across the port, and hence lowers the T-stoff pressure to the injectors. Conversely, if the T-stoff pressure is too low, the assembly is forced in the opposite direction until the shoulder on the shaft (29) bottoms. The inlet port is then wide open.

Control beyond this point is not necessary, as the design limits would then be exceeded. This condition would indicate that there is a probable failure in the T-stoff supply or an overpressure in the C-stoff pump discharge. The steam-generator regulator would have sensed this and made the proper corrections.

The above procedure insures that the two propellants are fed into the injectors at the same pressure. This maintains a relatively constant mixture ratio throughout the entire thrust range and, in turn, keeps the specific propellant consumption at a minimum consistent with the degree of throttling. The injection and ignition processes are also simplified.

In order to prime the T-stoff lines and injectors before actual operation, a 0.004-in.-deep flat is milled longitudinally on the outer surface of the T-stoff metering pistons from one inlet hole to the outside skirt. A small amount of T stoff thus by-passes the metering ports and fills the lines and injectors. A large enough pressure drop takes place across this by-pass slot so that the injector does not open. In this manner sudden surges of high pressure liquid is prevented.

C-Stoff Filter (See Fig. 38)

Two concentric, hollow cylindrical aluminum castings are placed at the entrance to the regulator. The walls of these castings are perforated. Around the periphery of each cylinder is wrapped a 130-mesh steel filter gauze held in place by wire. The smaller filter cylinder is inserted into the larger one and the subassembly inserted into the filter housing. Leakage at the joint of the two cylinders and between the outer cylinder and the recessed bore in the housing is prevented by synthetic rubber "O" rings. The two filter castings are held together by a hex-head bolt and the entire assembly held in the housing by a cast alunimum cover. The cover is bolted to studs in the filter housing by self-locking hex nuts. An AN-902-type gasket seals the joint.

C stoff from the motor cooling jacket enters port III (Fig. 30) and flows successively through both screens and out at the bottom into the center of the metering cylinder. All particles larger than 0.007 in. diam are filtered out and drop by gravity to the bottom of the housing. It is necessary to clean the filter after approximately 2200 lb of C stoff have flowed through. This is equivalent to about ten minutes of operation or about every two flights.

Later models incorporated only one filter, because it was found that larger particles could pass through the system without clogging or damaging the pistons or injectors.

Steam Generator Throttle

The steam-generator throttle is a valve mechanically linked to the main propellant throttle valve. (See Figs. 39 through 42.) Its purpose is to meter the proper amount of hydrogen peroxide to the steam generator for each stage of operation of the rocket engine.

The functions of this control are as follows:

1. Regulation of T stoff during idling position.
2. Metering the proper amount of T stoff for each stage of operation.
3. Limiting the maximum flow of peroxide and thus imposing an upper limit of thrust on the combustion chamber.
4. Acting as a safety shutoff for the turbine in the event of propellant-supply failure.

In order to permit a fuller understanding of the T-stoff regulator, a description of each of the parts shown in Figs. 39 through 42 is included. The steam-generator throttle is attached by bolts on the forward side of the engine thrust plate just below the steam generator. In this location it is readily accessible for maintenance or replacement.

Flare-type tube fittings (Fig. 40, view 32) are provided for the following: (1) T-stoff entrance from pump, (2) T-stoff exit to steam generator, (3) T-stoff leakage drain to turbine exhaust, (4) C-stoff pressure line, and (5) C-stoff leakage drain to pump suction. An additional screw plug is provided in the bottom of the housing for draining the T stoff from the main rotary control valve.

The functioning may be divided into four distinct phases: off, idling, operating, and quick shutoff.

Off Position

When set to the "zero" or "off" position, the pilot's throttle moves the lever arm on the T-stoff throttle valve to its zero position. The linkage is adjusted to insure complete closure of the metering cylinder before operation is attempted. This is obtained by blocking the five "T"-shaped slots in the hollow rotary shaft (Fig. 41, view 22a) by blanked-off spaces in the pressed-in sleeve surrounding this shaft. (See Fig. 40, View 22.) Leakage to the pistons is prevented only by the close fit between the cylinder and the stationary sleeve. Leakage to the outside is prevented by a packing gland and gaskets.

Idling (See Fig. 41, view 322)

The movement of the pilot's throttle to the idling position causes the actuating lever of the throttle to move to its first position. This is indicated on a card by the pointer attached to the lever. (See Fig. 42, view 62b.)

The two "T" slits (4) nearest the actuating lever in the rotary valve (shown on the right, Fig. 41, view 22a) are now lined up with the ports in the fixed sleeve, and permit entry of T stoff into the inside of the idling piston. The other three slits are still blanked off.

The starter button or the gravity-tank hand valve (depending upon which version of the 109-509 engine is being used) is now actuated and the pumps come up to idling speed.

Peroxide, under pressure, flows into the rotary valve through a filter. Pressure is applied to the underside of the cutoff piston through a drilled hole (5) in the housing (Fig. 40, view 22), and provides an upward force. This is balanced by the combined force of a small spring (to insure a full open position of the piston in the "off" position) and the pressure of the C stoff from the pump.

The peroxide flows from the metering cylinder to the idling piston (right hand vertical housing, Fig. 40, view 22). As may be seen from this and Fig. 42, view 323a, this chamber consists of a drilled hole in the valve housing, into which a cylindrical sleeve is pressed. Radial holes in the sleeve are connected to a horizontally drilled hole (2) from the T-stoff outlet fitting. The floating, idling piston is inserted in this sleeve and located by a shoulder on its uppermost portion. It is held in its down, or full open, position by a spring acting through a retainer which bears on top of the piston. The spring force is adjustable by means of a set screw, and motion is limited by an additional set screw. As normally adjusted, T-stoff pressure must reach 284 to 355 psi before the piston begins to move upward.

The initial blocking of the idling piston in the open position permits the full flow of T stoff to the steam generator, and hence the rapid build-up of pump rpm to idling speed. Overspeeding is prevented by the upward movement of the piston against the spring. This causes partial blocking of the piston outlet holes. The holes are so positioned as to pass to the steam generator an amount of peroxide, at approximately 320 psi, sufficient to provide steam for idling.

Operating (See Fig. 41, view 323)

Further movement of the pilot's throttle to the first stage of thrust rotates the T-stoff metering cylinder to the required setting. This partially aligns the metering cylinder main slots (Fig. 41, view 22a, right hand slots) with the holes in the stationary sleeve. It also partially blocks off the two idling slots. This blocking has little or no effect upon the turbine speed. Because the restriction decreases the pressure acting on the idling piston, the spring forces it downward, uncovering more of the outlet. The outlet pressure drop is decreased, so that the net drop, and hence the flow, remains practically constant.

Part of the peroxide also flows from the metering cylinder through the vertical hole (1) in the housing. (See Fig. 40, view 22.) It combines with that coming from the idling piston in the horizontal connecting hole (2), flows through the cutoff piston passageway, and enters the steam generator. More steam is produced and the turbine rpm increases.

The main slots (3) are so proportioned that additional rotation uncovers more area and allows a greater flow of T stoff. Further rotation also continues to close the idling slots (4). At the maximum thrust position (Fig. 41, view 324), the operating slots are fully uncovered, while the idling slots are almost entirely blocked off. The index pointer now points to the maximum thrust position.

The only changes necessary for conversion of this control as used in the 109-509A-1 engine for use at increased thrust in later versions (the 109-509A-2, C and S) are a remachining of the main slots in the rotary valve and a widening of the annular groove in the shutoff piston. This would permit more T stoff to flow to the steam generator, increase the speed of the turbine, and hence increase the pump output.

The proper sizing of all the metering holes and slots was done empirically. The tolerance deviations of individual valves are compensated for by the numerous adjustments possible.

Quick Cutoff Safety

In order to prevent overspeeding and destruction of the turbine in the event of the interruption of supply of either propellant, a cutoff safety valve is provided in the T-stoff throttle. Failure in the supply of T stoff would, of course, stop the turbine, because the steam generation supply is derived from the T-stoff pump delivery line. Failure of the C-stoff supply from depletion or line breakage is compensated for by the cutoff piston previously mentioned and shown in Fig. 40, view 22 (left hand piston); Fig. 41, view 22c; and Fig. 42, view 324a. This is accomplished in the following manner:

C stoff from the pump enters through a fitting on the top of the left hand vertical housing (Fig. 40, views 27 and 22) and is returned to the tank through a restricted drain hole in the tube below the inlet. The pressure acts against the synthetic rubber (Buna) diaphragm, through a poppet and stem to the floating piston, and keeps it in its full-down, or open, position. Leakage of the C stoff into the spring housing is prevented by the diaphragm. Leakage of the T stoff past the piston and into the upper housing is prevented by a synthetic rubber, bellows-type seal. Any leakage past the piston is led to the common drain and dumped into the turbine exhaust.

If, for any reason, the C-stoff pressure fails, the cutoff piston is forced upward by the pressure of the T stoff acting on its lower side. The T-stoff part is completely blocked off and the turbine stops. This is a very simple method of providing a positive safety shutoff without the added complexities of pressure switches, relays, and electrical circuits.

Effect of Throttling on Specific Impulse

HWK 109-509

The 109-509, in common with the systems previously discussed, achieves throttling by reducing the chamber pressure. The general effects of throttling on the specific impulse of the 109-509 follow the usual pattern: the first 25% of throttling causes relatively little decrease in efficiency, but after that point the worsening of performance becomes definite. Figure 43 plots the predicted specific propellant consumption for the 109-509A-1 as a function both of thrust and of altitude.

The sea-level curve displays the almost doubled specific consumption through the extremes of the throttling range. However, it should be noted that throttled operation beyond 75% of full thrust was hardly contemplated at sea level, because of the thrust-available - thrust-required relationship of the aircraft, and because of the usual flight program. Throttled performance was to be expected at rather high altitudes, and it will be seen that the worsening in performance at high altitude is less than that at sea level. This phenomenon recalls the importance of the nozzle coefficient, C_F, and again points out the fact that the nozzle coefficient is not a function of the absolute chamber pressure, but rather of the ratio between the chamber pressure and the ambient pressure.

Curves such as Fig. 43 do not permit a determination of the minimum stable operating range. These are set, rather, by injector-design considerations, and are covered in detail in section 51-0-12C (Vol II) of this report. For example, the early version of the 109-509A-1 was designed to be throttleable to 330 lb. However, the deterioration in injector performance at this thrust was such that the lower limit was raised to 440 lb.

The throttling performance of the 109-509 will be compared with the other systems under analysis in the summary section of this report, below. The 10:1 throttling range for a single motor, achieved in the 109-509, was a very commendable achievement. The generality of combustion chambers, even in experimental development, was rarely throttleable beyond 4:1, recourse being had to two or more chambers when a wider throttling range was desired. In part, this is achieved through the ingenious control and regulation system employed.

Thrust Control by Variable Throat Area

The earlier sections of this report have called attention to the parameters affecting specific impulse during throttling. It was noted that the usual throttling method of decreasing the chamber pressure results in a poor nozzle coefficient. This fact was recognized by BMW, who proposed to vary the throat area instead, thereby maintaining the chamber pressure and, hence, the value of the nozzle coefficient. The development of the "throat plug," however, was not carried beyond the proposal and patent application stages. In the case of the patent (discussed below), a number of automatic control features are also proposed, but the point of major interest is the suggestion that a cooled pylon be run down the length of the combustion chamber to vary the throat area. 14/

Figure 44 proposes a method of infinitely controlling the thrust of a rocket engine by means of ram pressure (velocity of vehicle). The desired thrust value is preset by the pilot's throttle lever acting through a linkage to the vertical rod on the bellows (7). Precompression of the bellows produces a high thrust setting, and pre-expansion results in a low thrust. After thrust has been initiated in the chamber (6), part of the combustion gases are led through pipe (12) into the pneumatic pilot servo cylinder (9). Until the proper ram pressure (vehicle velocity) has been reached in the aneroid gage (8), the preset compression of the bellows (7) keeps the control piston in the pilot valve (9) in its "down" position. The gas pressure from the chamber is led to the top of the main servo piston (10) and forces it downward. This motion is transmitted through the lever (11) to the nozzle plug (1) and its holder (4), and pulls the plug away from the throat. The motion is also transmitted, through means not shown, to a propellant-flow regulator, and permits more propellant to enter the chamber.

The thrust continues to increase until the forward velocity of the aircraft is such that the ram air acting through the inlet scoop of the gage (8) overcomes the precompression of the bellows (7). The bellows then forces the piston in the valve (9) to move upward, and cuts off the supply of gas to the piston (10). This fixes the position of the plug (1) and maintains the thrust at that setting. If the velocity exceeds this value, the bellows (7) moves further upward. Chamber gases are then allowed to flow to the under side of the piston (10), forcing it upward and restricting the chamber throat area by motion of the plug. The thrust decreases, and the system returns to its proper setting.

In order to prevent such a thrust regulator from continually "hunting," the cylinder on both sides of the piston (10) is vented through restricted bleeds. When the piston of the pilot valve (9) uncovers

14/ APJ No. F 5-45.

the port of either side of the main servo (10), the gas vents slowly enough to prevent overshooting the correct setting. Some oscillations may occur, but these will be quickly damped out.

Figure 45 shows a two-stage thrust control similar in operation to that described above. Maximum thrust is attained in the position as shown. When a preset velocity has been reached, the ram air pressure forces the bellows (7) upward and unlatches the valve lever (14). This lever is pulled to the right by the spring (13), and opens the valve in the line (12). The chamber gases then flow through the pipe (12) and force the piston (10) toward the chamber, thereby partially restricting the nozzle with the plug (1). Only two positions are possible with such a device, and repeat use without manual reset is not feasible.

The throat plug throttling system consists of a pylon positioned in the throat of the combustion chamber and cooled by the flow of one of the propellants. It was obvious that the regenerative cooling here provided would not permit a reasonable service life. Interrogation of foreign scientists has also revealed that such a pylon may be cooled by the use of porous material or even that it may be used as a variety of counterflow injector in a manner reminiscent of the early Peenemunde systems.

The mechanical means for obtaining alignment and concentricity would appear to present additional points of difficulty. The seriousness of the problem would depend in no small measure on the length of the combustion chamber. It is, hence, linked closely to the development theory for combustion chambers, discussed in section 51-0-12A (Vol. I) of this report. The longer the combustion chamber, the more serious the concentricity problem.

The throat pylon may also be expected to have its effect on injector design. Inasmuch as the central portion of the head is taken up with the mechanism for supporting and moving the throat plug, the injector must of necessity be disposed around the sides of the head. This would force the use of a multiplicity of injectors, with attendant design complications.

Despite the criticisms that may be made against throat throttling, it is nevertheless of considerable interest. Indeed, experimental motors with throat throttling have been constructed in this country.

SUMMARY

An analysis of the practical impact of throttling on specific impulse should consider whether, in a given application, the attainment of optimum specific impulse through a wide throttling range is worth the difficulties involved in achieving it. The answer to this question will vary with the mission of the aircraft, but generalized analysis may provide a number of indications on this point.

The foregoing studies of the variation in specific propellant consumption with throttling have encountered curves computed for various altitudes. Invariably, these have shown that the degree of deterioration in efficiency is much less in throttled performance at altitude than it is at sea level. Analysis has shown that this is due to the improved nozzle coefficient, which is obtained automatically with the decreased ambient pressure at altitude.

If consideration is given to the thrust-available - thrust-required curves for representative guided missiles and aircraft, it is clear that, except in special cases, no requirement for throttling exists near sea level, since there acceleration and climb are all-important.

Figure 46 presents the throttling vs. specific propellant consumption relationship at sea level for a number of representative systems. Predicted performance curves are given for the P 3390C, the 109-708B, and the 109-558, while actual test results are given for the 109-509A and the 109-548. It is noted that the over-all consumptions of the three pump-type systems are higher than those

quoted for the respective pressure systems. (The propellant combinations of the P 3390C, the 109-708B, the 109-558, and the 109-548 are identical, and their performances are, therefore, comparable.) This may be attributed, in part, to the fact that the pump type systems are charged with the specific propellant consumption of their respective steam generators.

An evaluation of Fig. 46 should also take into account the fact that the P 3390C and 109-708B curves are each based on a single engine. This is done to make possible a valid comparison. In the actual case, the P 3390C and the 109-708B each had two motors, permitting the throttling range to be split between a cruise and a climb chamber.

Figure 47, which is a recalculation of the basic data presented in Fig. 46, shows the percentage increase in propellant consumption for sea level as a function of throttling. It is noteworthy that all the curves fall very closely together. The curves based on theory do not show the steep increase in specific propellant consumption at the extremes of throttling - an indication of a certain degree of optimism on the part of the engineers. It may be desirable to correct the theoretical values by the evaluation parameter, X, according to Peenemunde practice as described in APJ Report No. 51-0-12A (Vol. I). This report defines X as the ratio of the actual to the theoretical jet velocity, and since X varies with the pressure ratio P_c/P_e, it follows that new values must be calculated for each value of the pressure ratio. The direction of change of the parameter, X, will produce a more rapid worsening of the specific propellant consumption in the extreme throttling range, where the value P_c/P_e is relatively small compared with the initial value.

Attention has already been called to the fact that throttled performance is more characteristic of altitude requirements than of sea level operation. Accordingly, altitude throttling parameters are of interest. Curves for percentage increase in specific propellant consumption with throttling at approximately 30,000 ft altitude for the 109-509A and the 109-558 engines are plotted in Fig. 48. A comparison of this data with that presented in Fig. 47 discloses an extreme improvement in the decrease of permissible throttling before the propellant consumption drastically increases. For example, if 20% increase in specific propellant consumption is set as the maximum acceptable, then the generality of sea-level engines may be throttled to approximately 40% - 50% of full thrust before this value is attained. By contrast, throttling may be carried to 20% - 30% of full thrust at altitude. The reason for this is again to be found in the maintenance of the nozzle coefficient due to the decreased backpressure.

The data available regarding the effect of control systems on specific impulse is not sufficient to permit a deductive analysis. The general German choice of speed control acts to minimize the steam-generator requirements, and then cuts the steam-generator propellant consumption with throttling. Unfortunately, the throat-plug type of throttled motor was never carried to the stage of practical test. It is believed that it would have improved the throttling range.

The general conclusion of the analysis of pump control and throttling, together with the effect on specific impulse, indicates that a very high degree of flexibility is available to the designer, and that the specific requirements of the mission are of decisive importance. It may well be that careful consideration of throttling requirements as a function of flight program and operating altitude will disclose that the conventional performance curves obtained by chamber-pressure throttling are satisfactory for the usual range, without having recourse to complicated and possibly hazardous controls.

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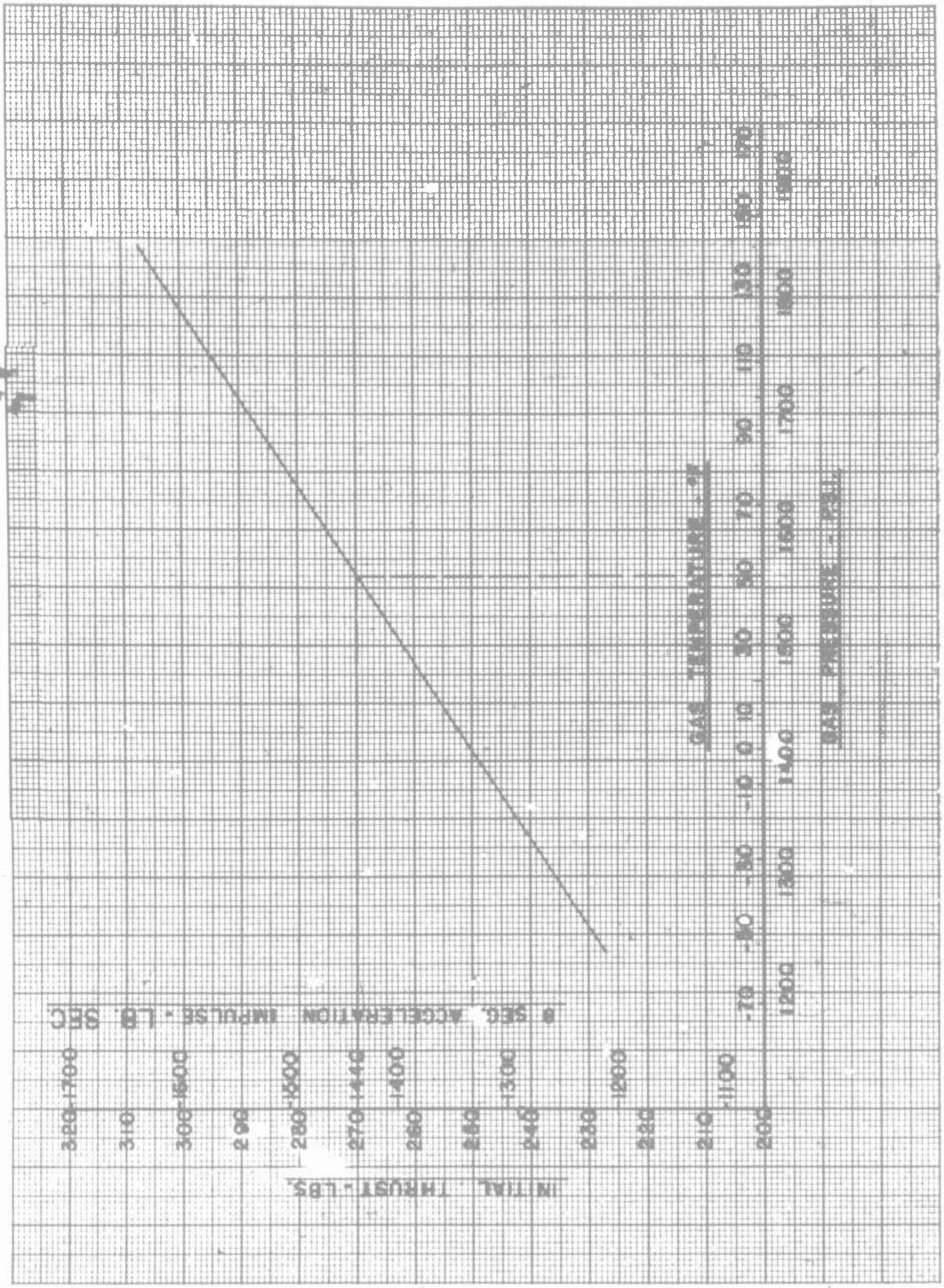


Fig. 1 - Initial Thrust and Acceleration Impulse as a Function of Compressed Gas Pressure and Temperature - BMW 109-548

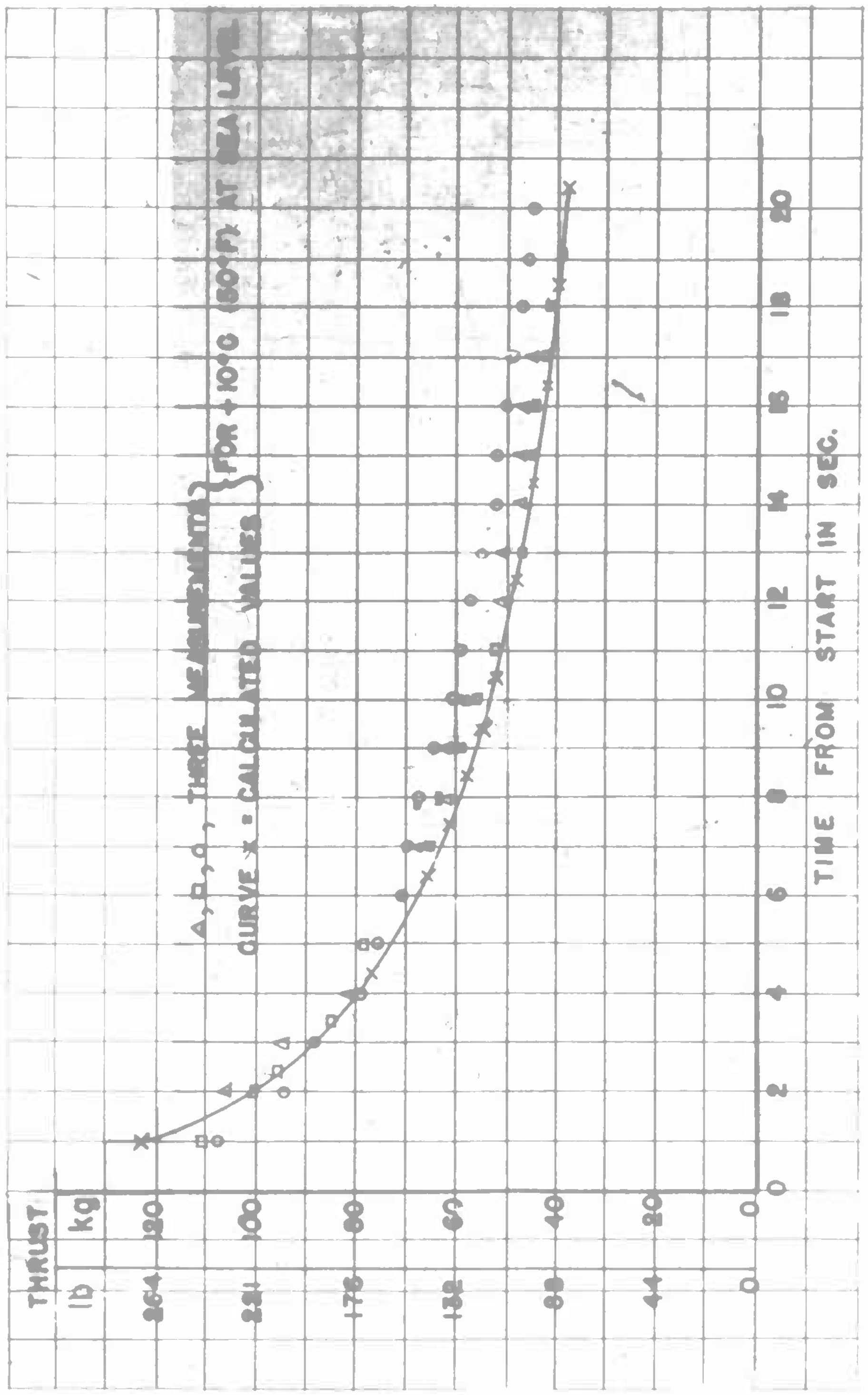


Fig. 2 - Comparison of Calculated and Measured Values - For 50°F at Sea Level - BMW 109-548

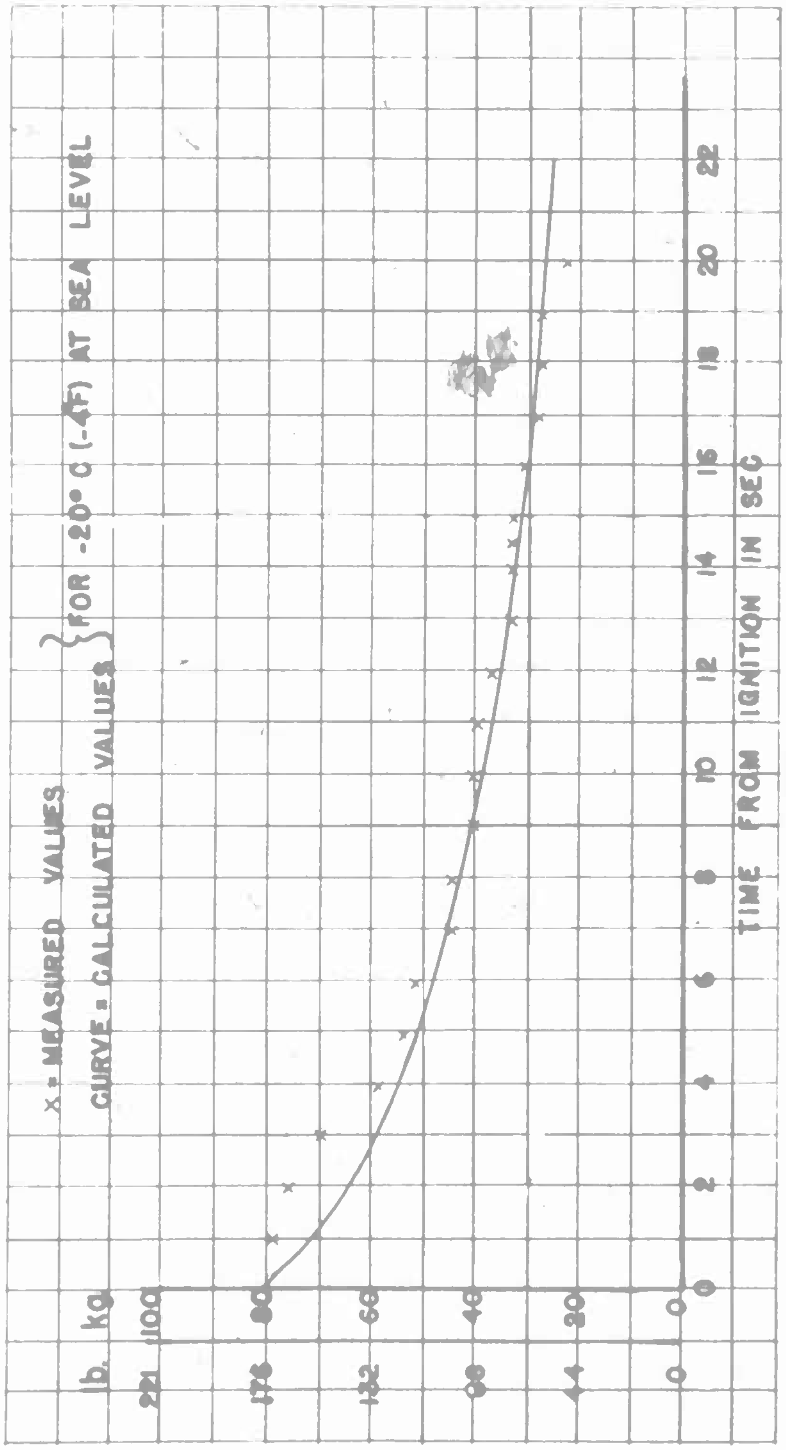


Fig. 3 - Comparison of Calculated and Measured Values - For -4°F at Sea Level - BMW 109-548

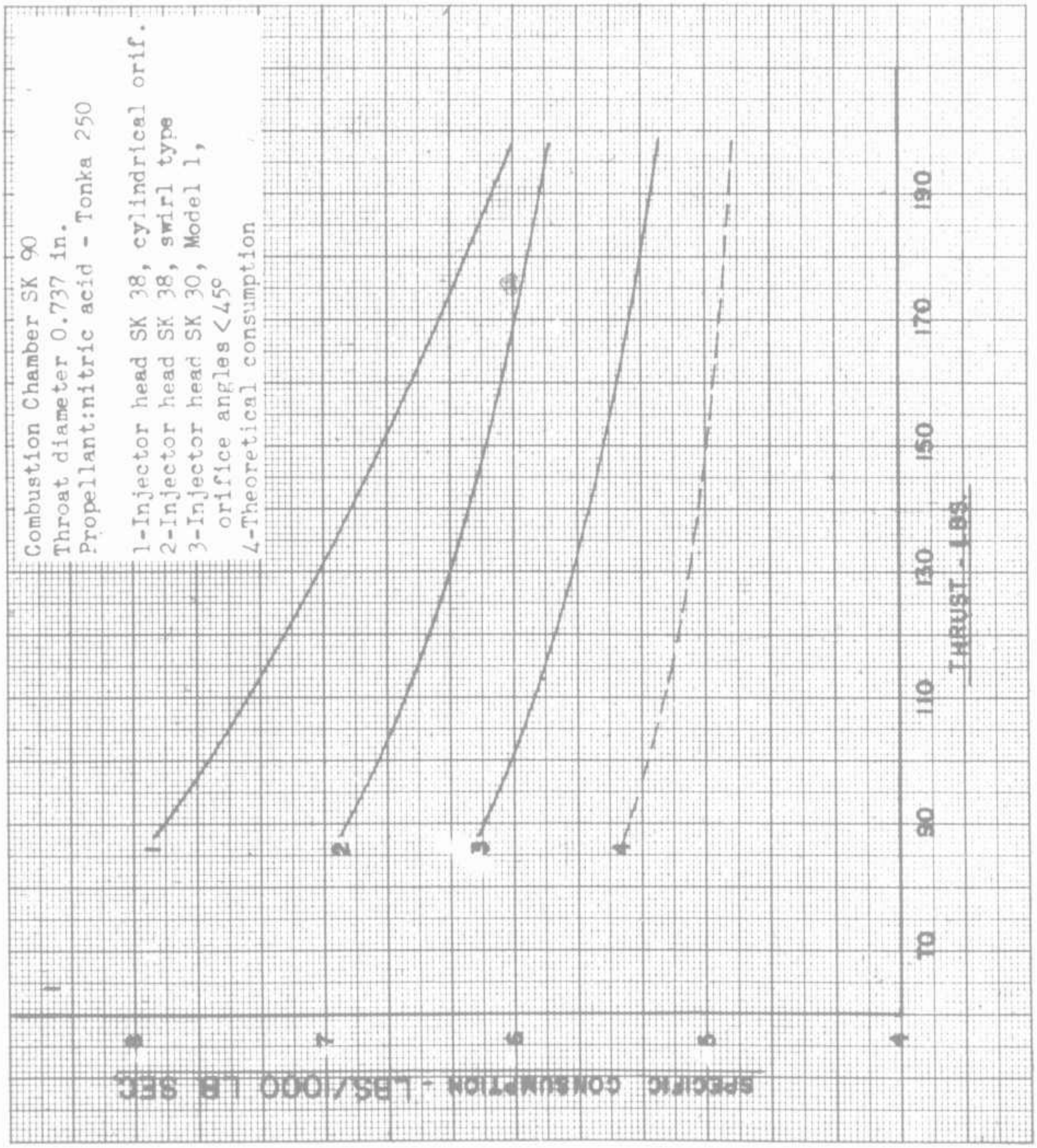


Fig. 4 - Variation of Specific Propellant Consumption With Thrust - BMW-100-548

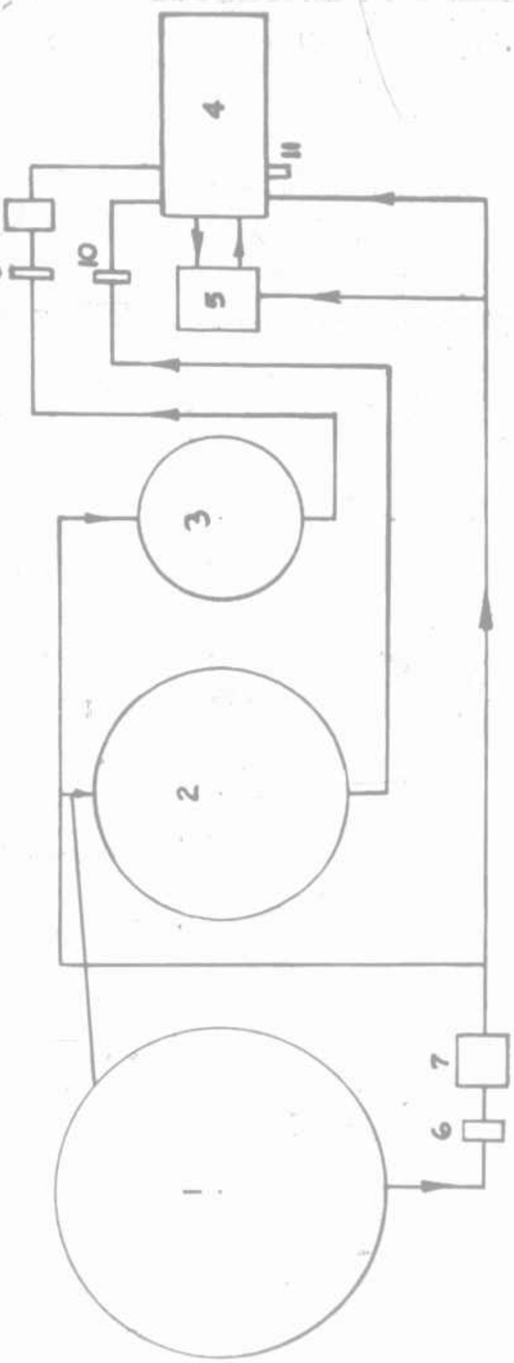


Fig. 5 - Schematic Arrangement - Schmidding SG-24 (APJ Drawing No. 051-900-22-00)

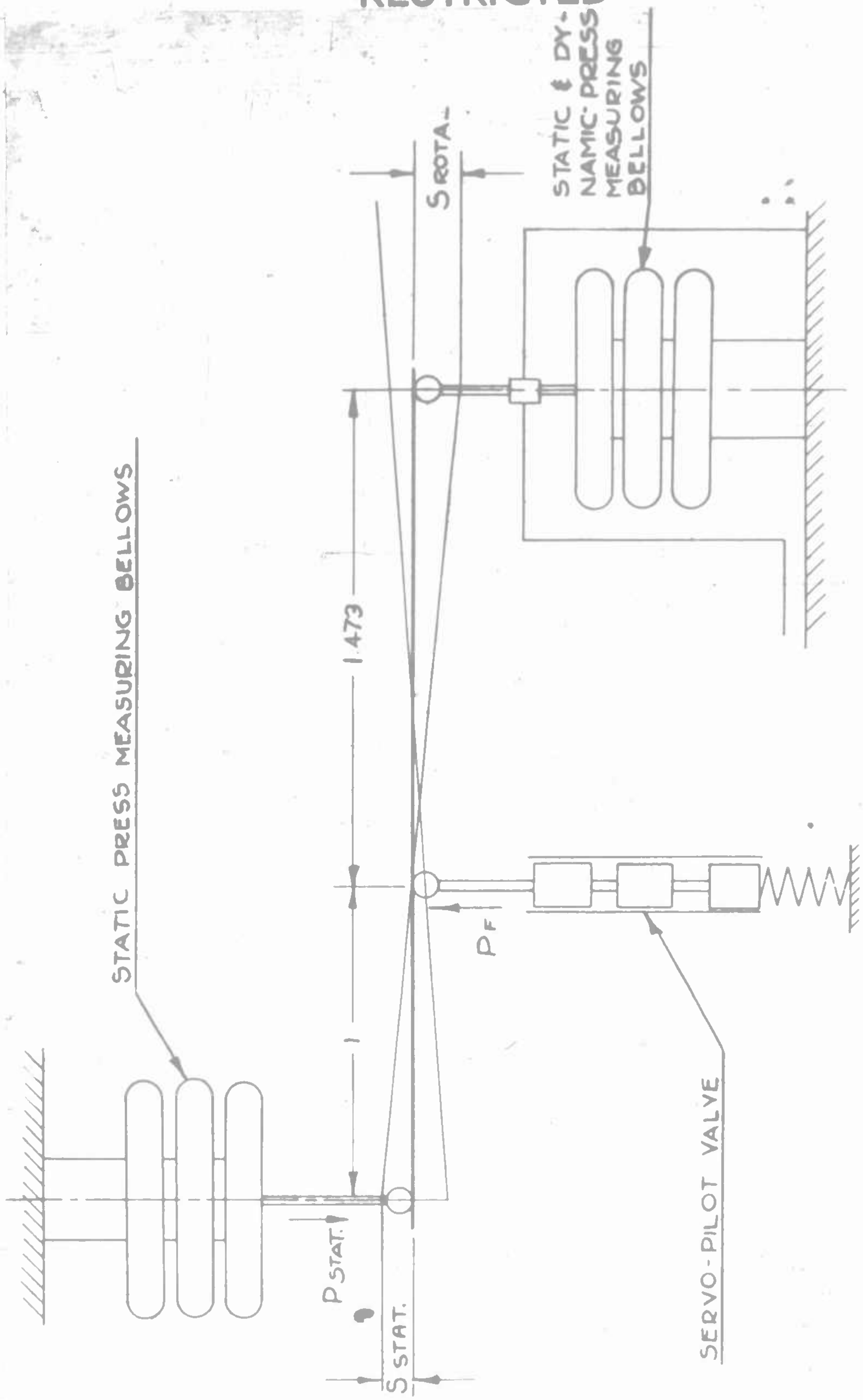


Fig. 6 - Schematic Arrangement - Mach Number Regulator (APJ Drawing No. 05-950-03-00)

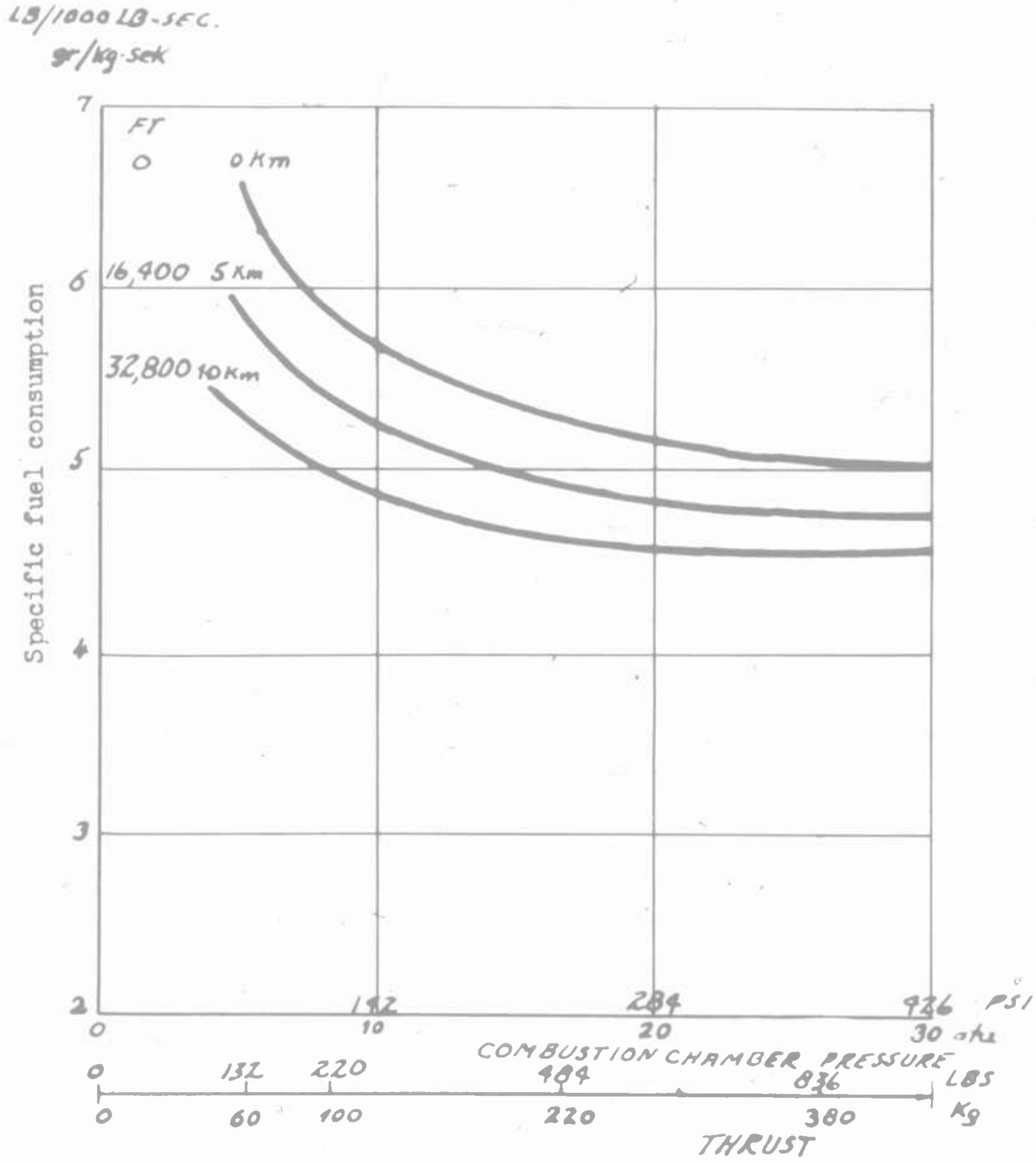


Fig. 7 - Variation of Specific Propellant Consumption
With Thrust - BMW 109-558

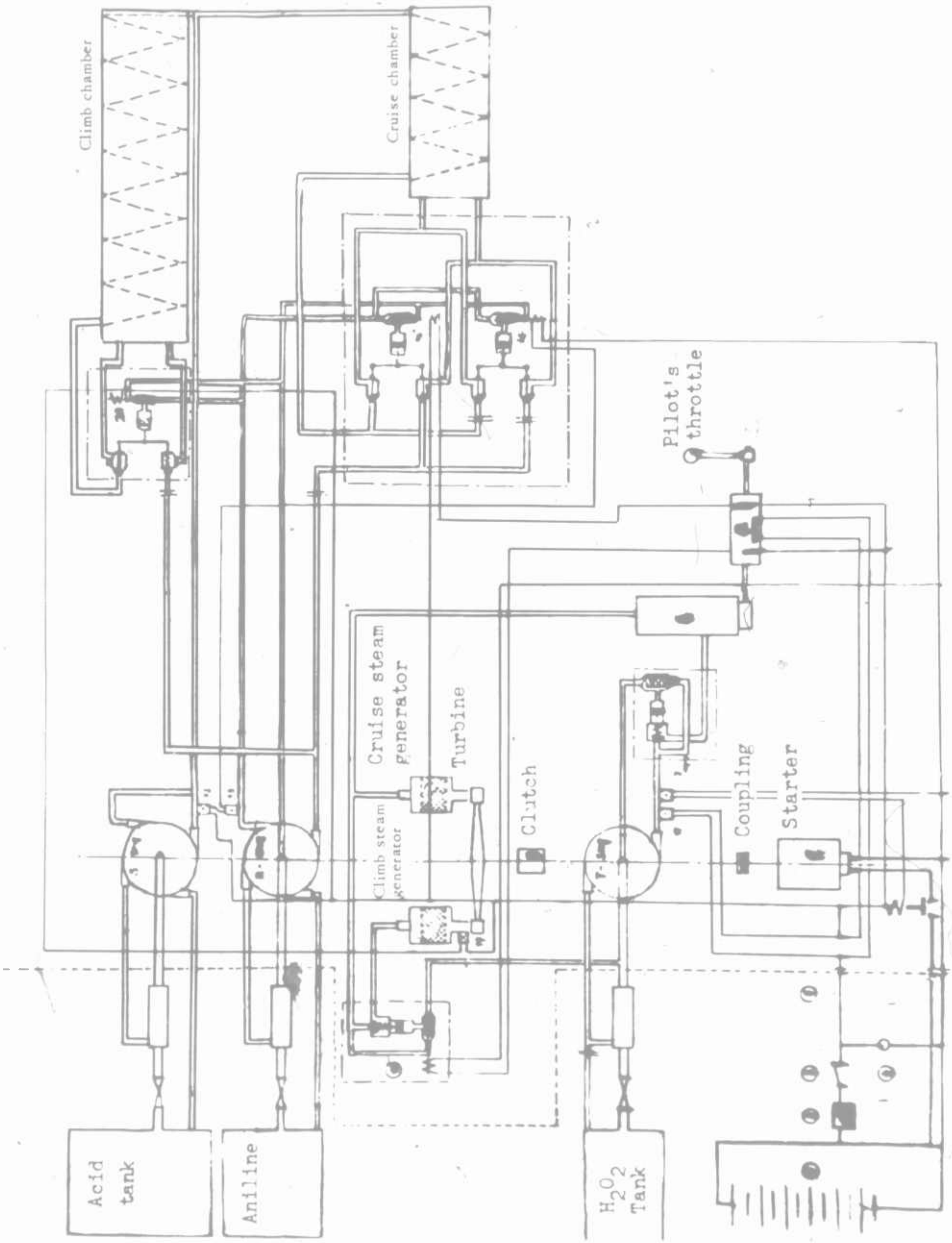


Fig. 8 - Control Schematic - P 3390C German Drawing No. 3390-C/SK 1157 (APJ Drawing No. D-3390C-1)

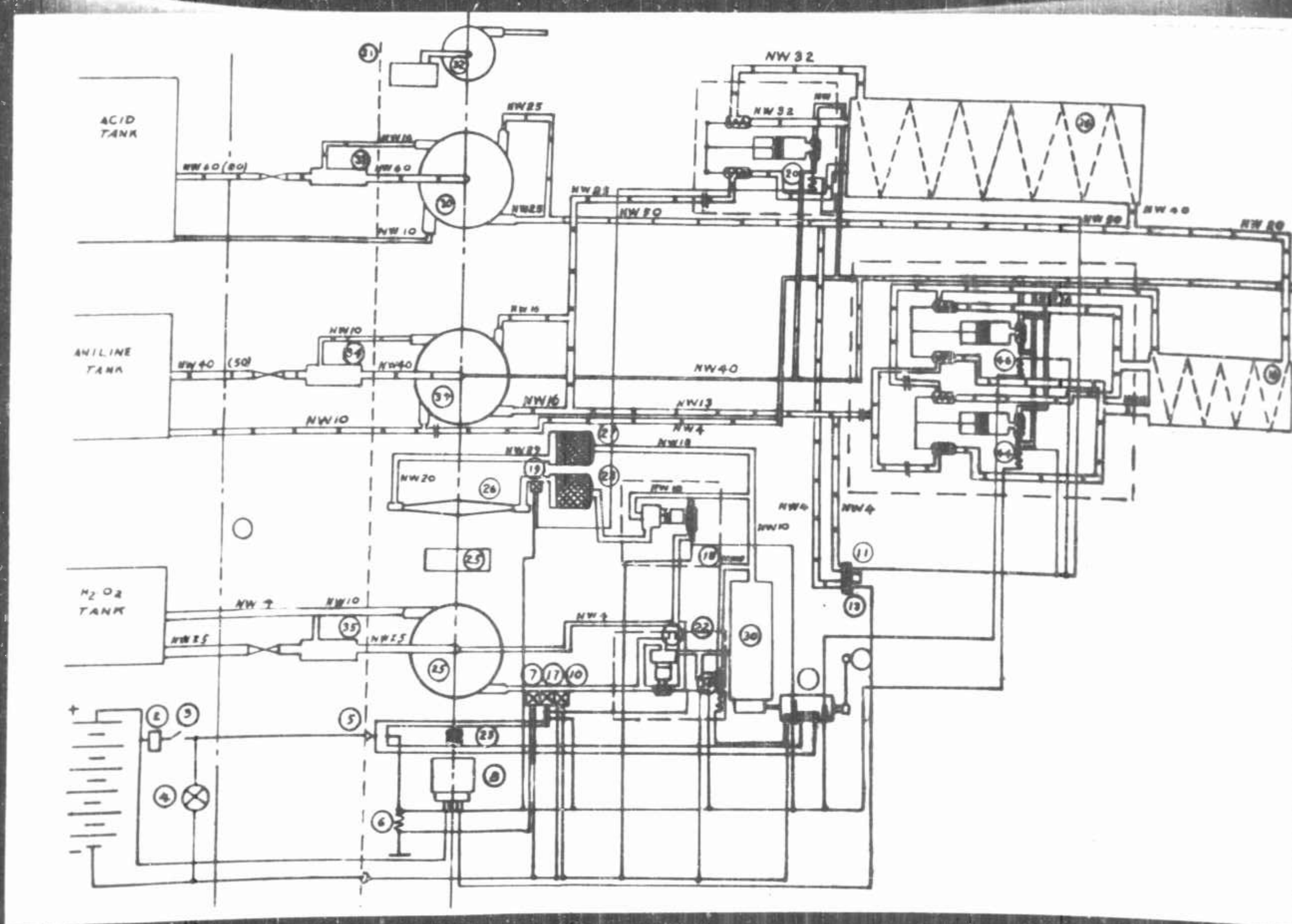


Fig. 9 - Control Schematic - P-3390C German Drawing No. 3390-C/SK 1158

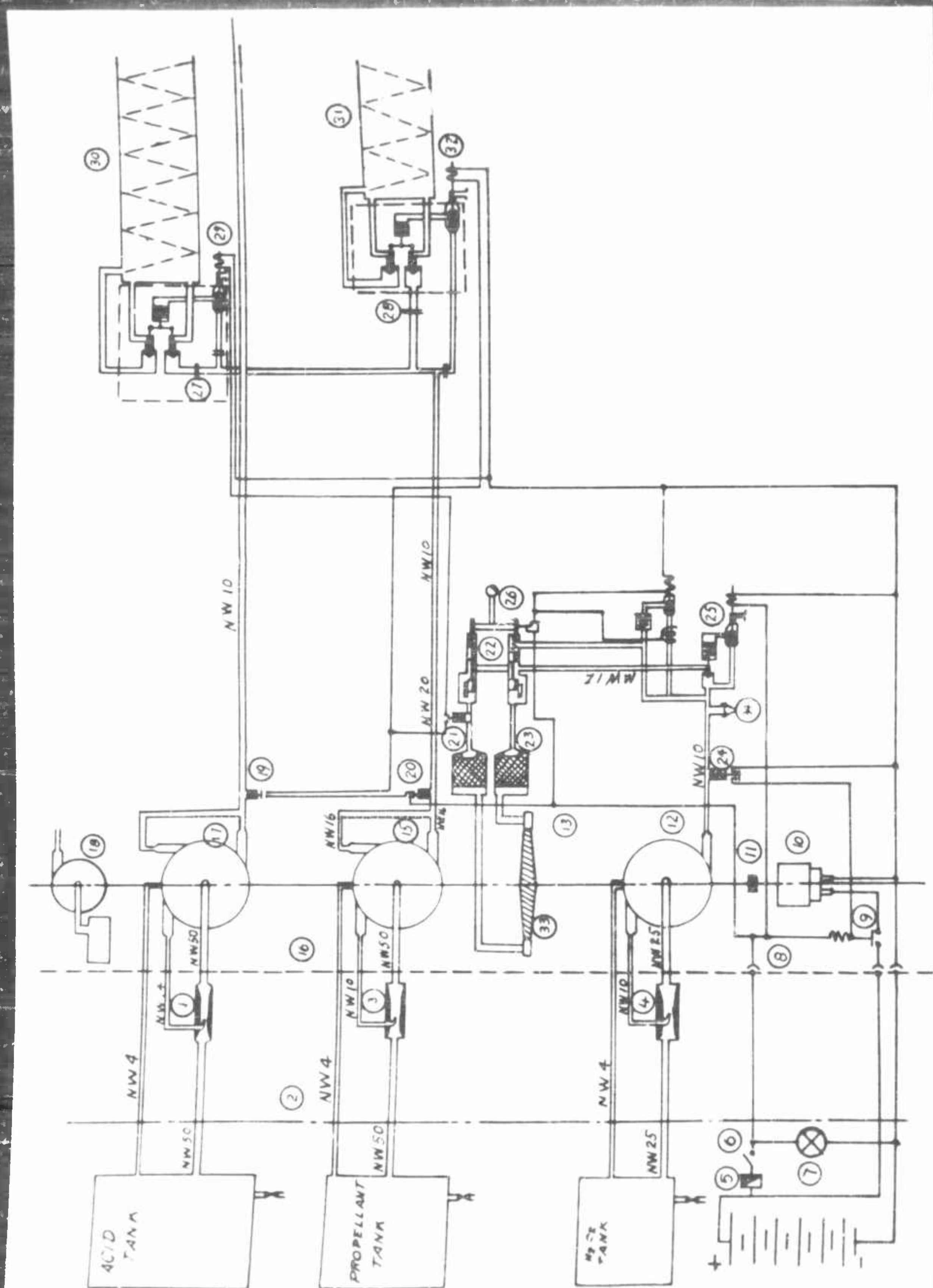


Fig. 10 - Control Schematic - P 3390C German Drawing No. 3390-C/SK 1248 (APJ Drawing No. D-9-3390C-2)

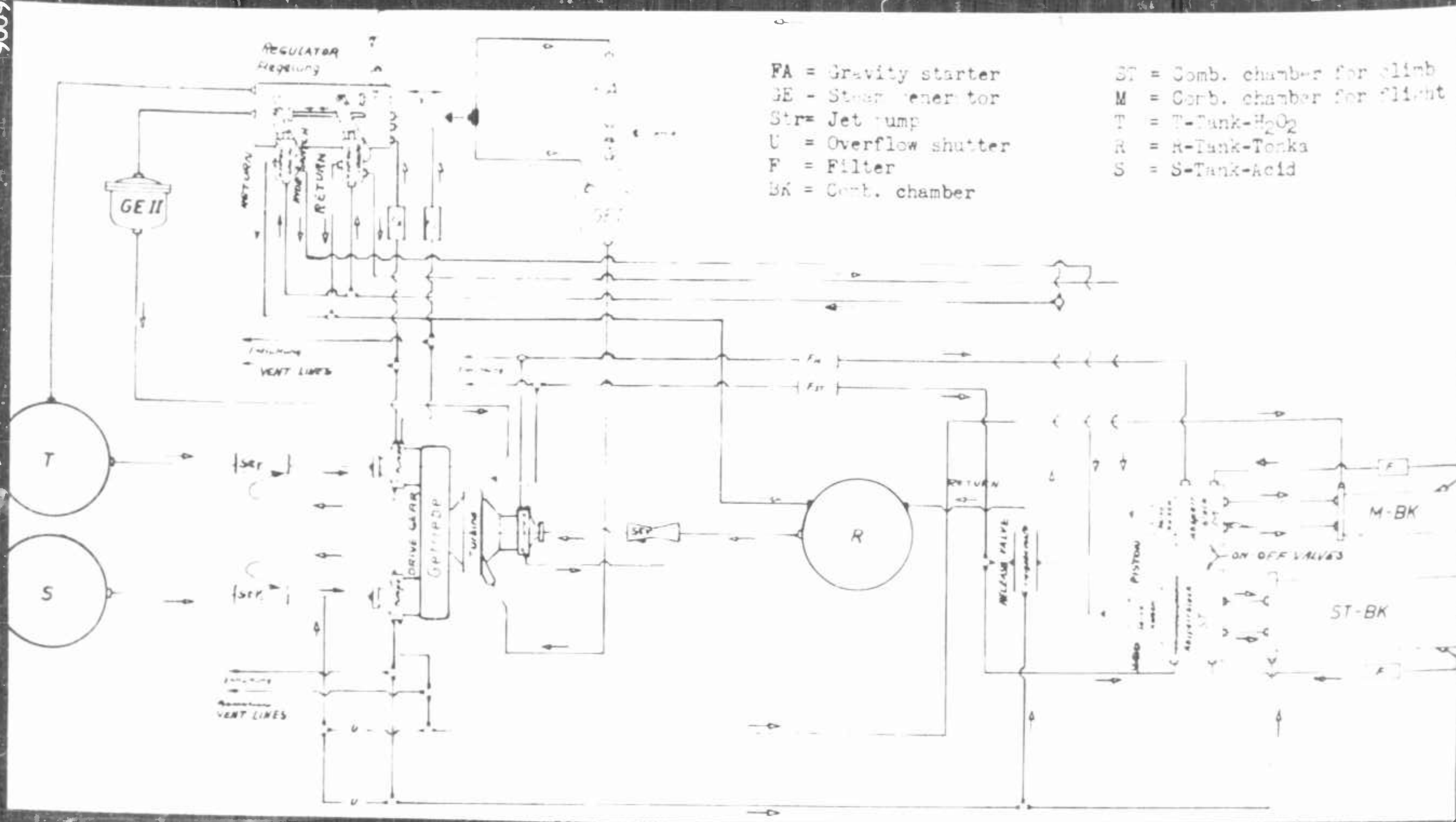


Fig. 11 - Control Schematic 109-708A German Drawing No. ERK 12274 (APJ Drawing No. D-9-708A-1)

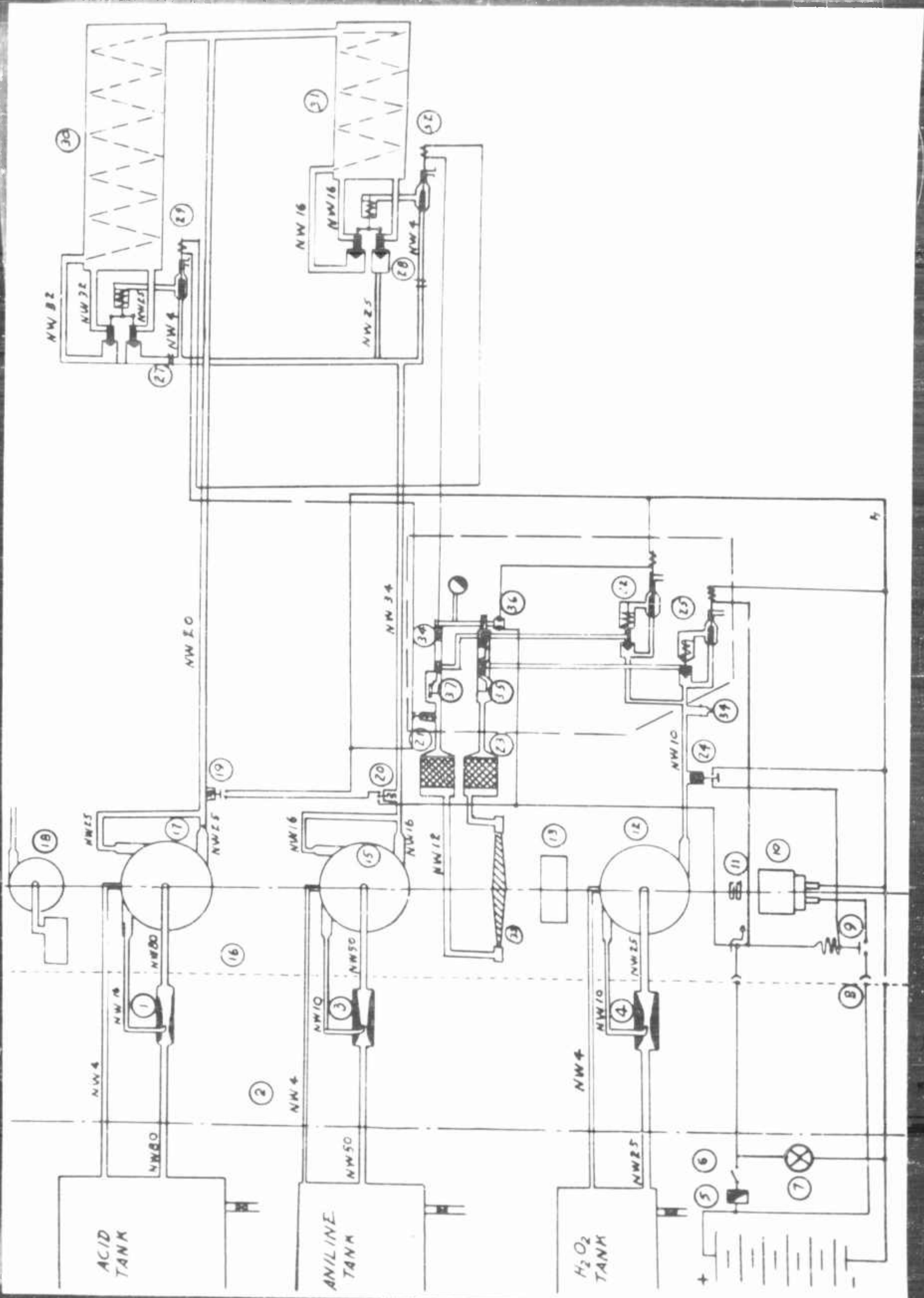


Fig. 12 - Control Schematic - P 3390C German Drawing No. 3390-C/SK 1297 (APJ Drawing No. D-9-3390C-3)

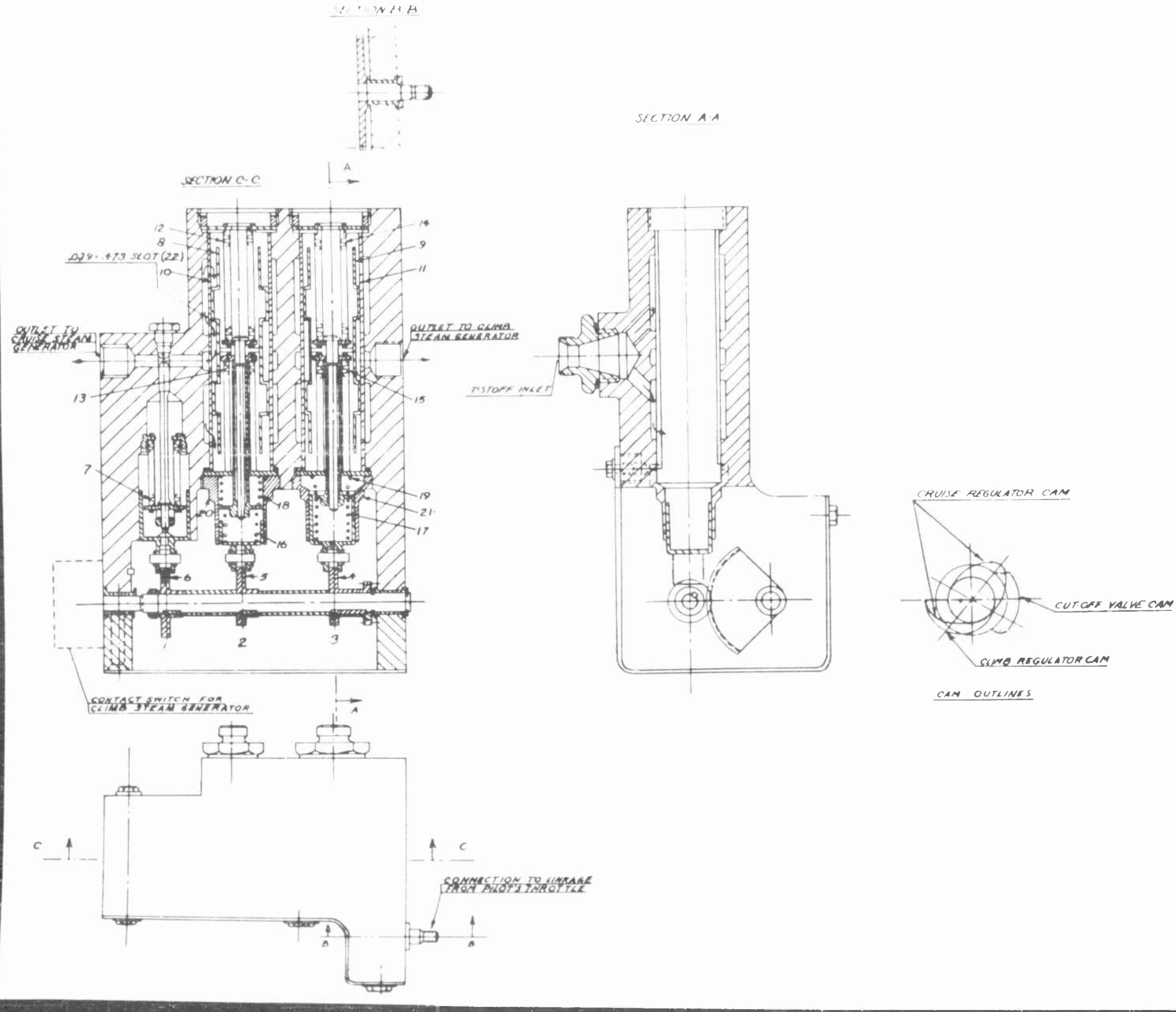


Fig. 13 - Regulator Proposal - P 3390C (APJ Drawing No. D-5-3390C-7)

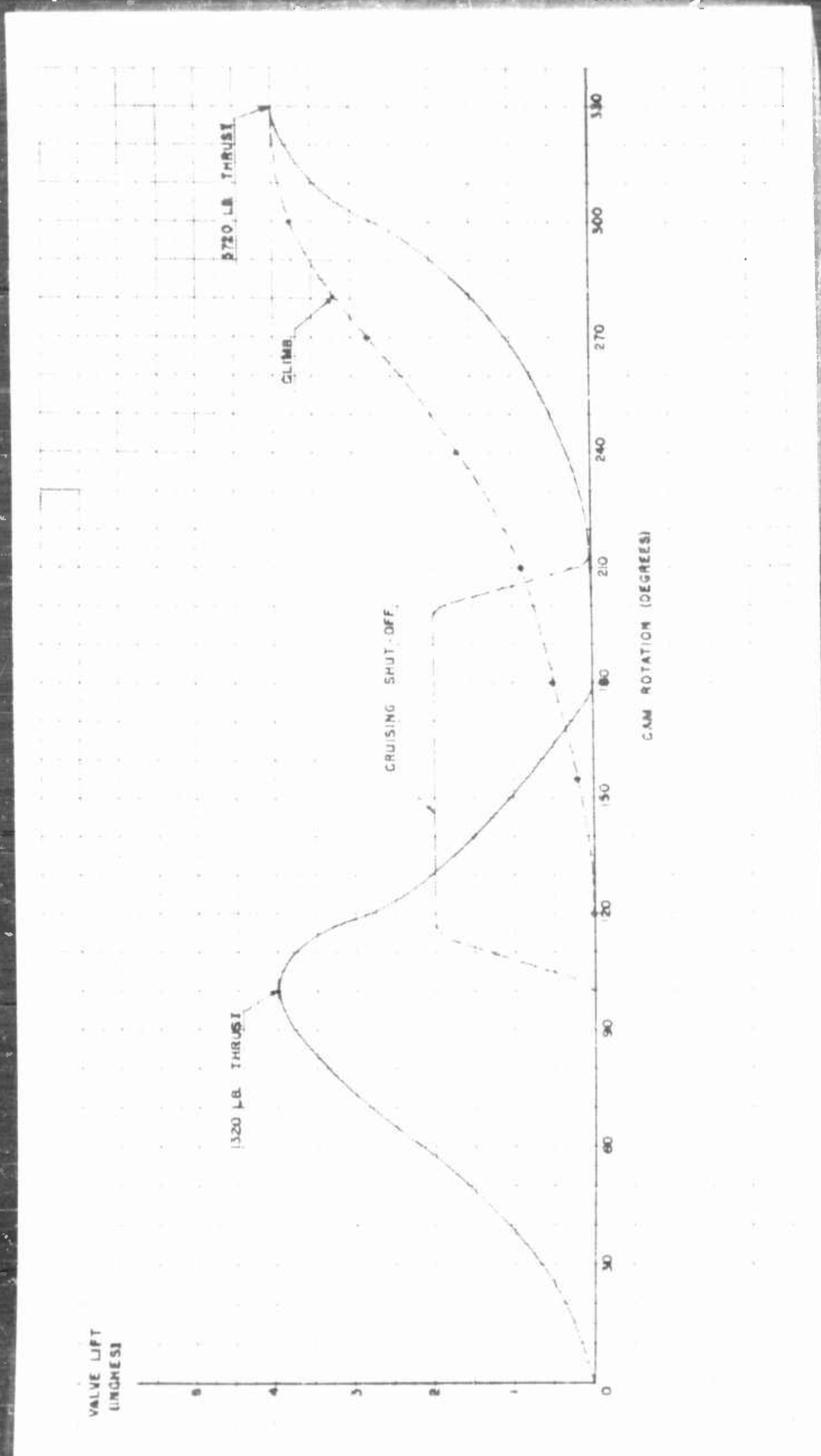


Fig. 14 - Cam Synchronization - P 3390C T-Stoff Regulator

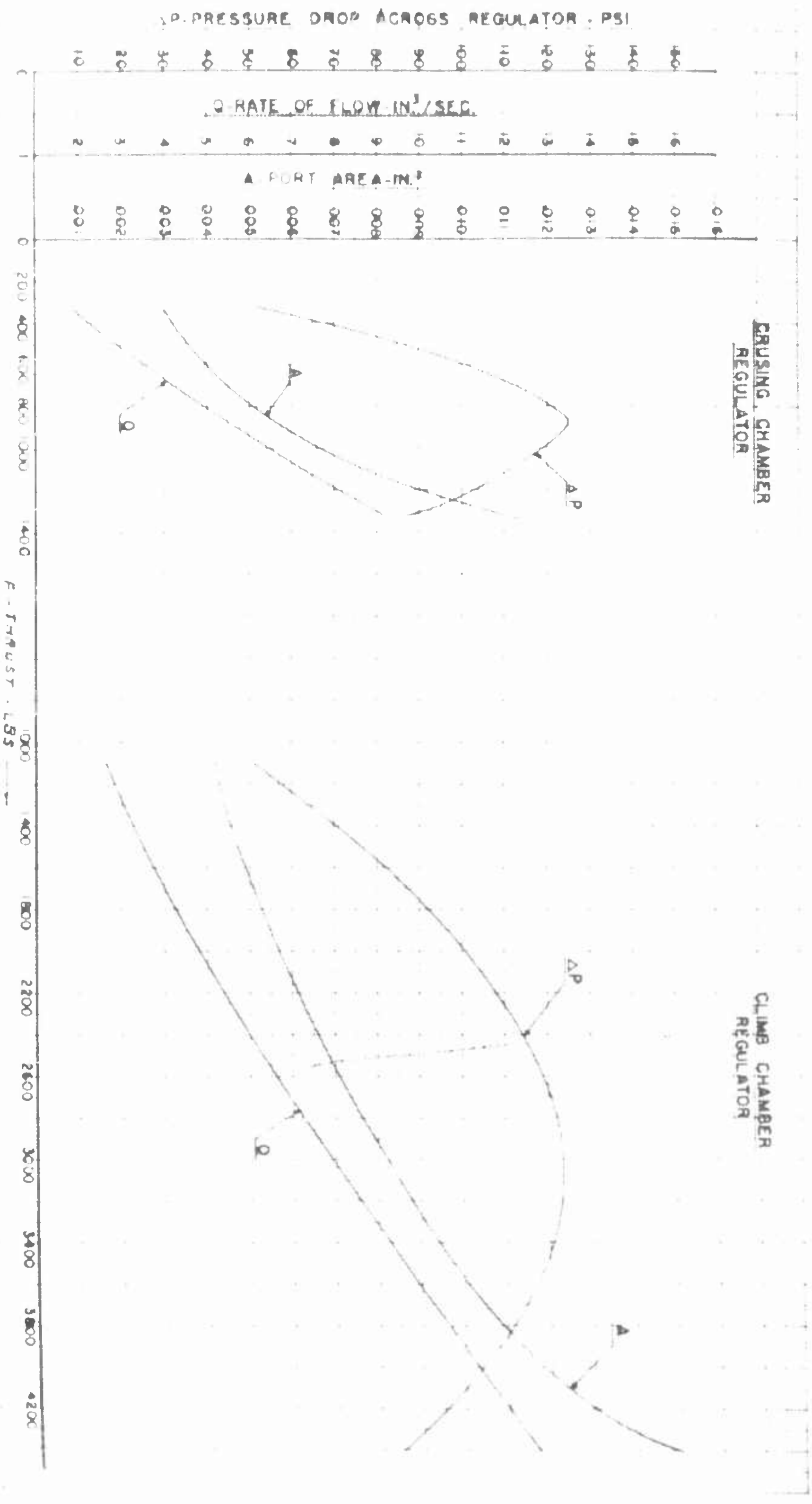


Fig. 15 - Regulator Performance - P 3390C/SK 1297

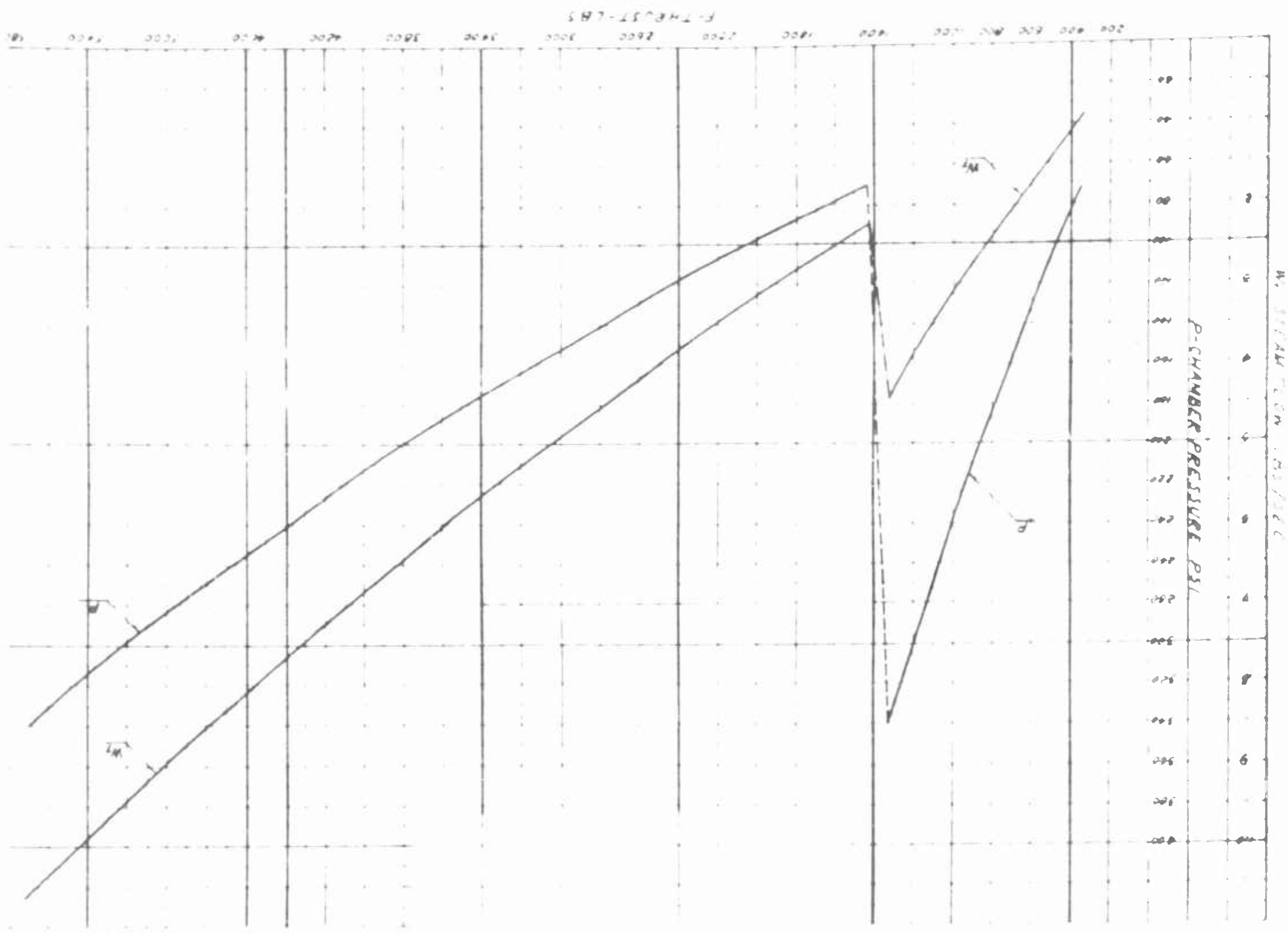


Fig. 16 - Steam Generator Performance - P 3390C/SK 1297

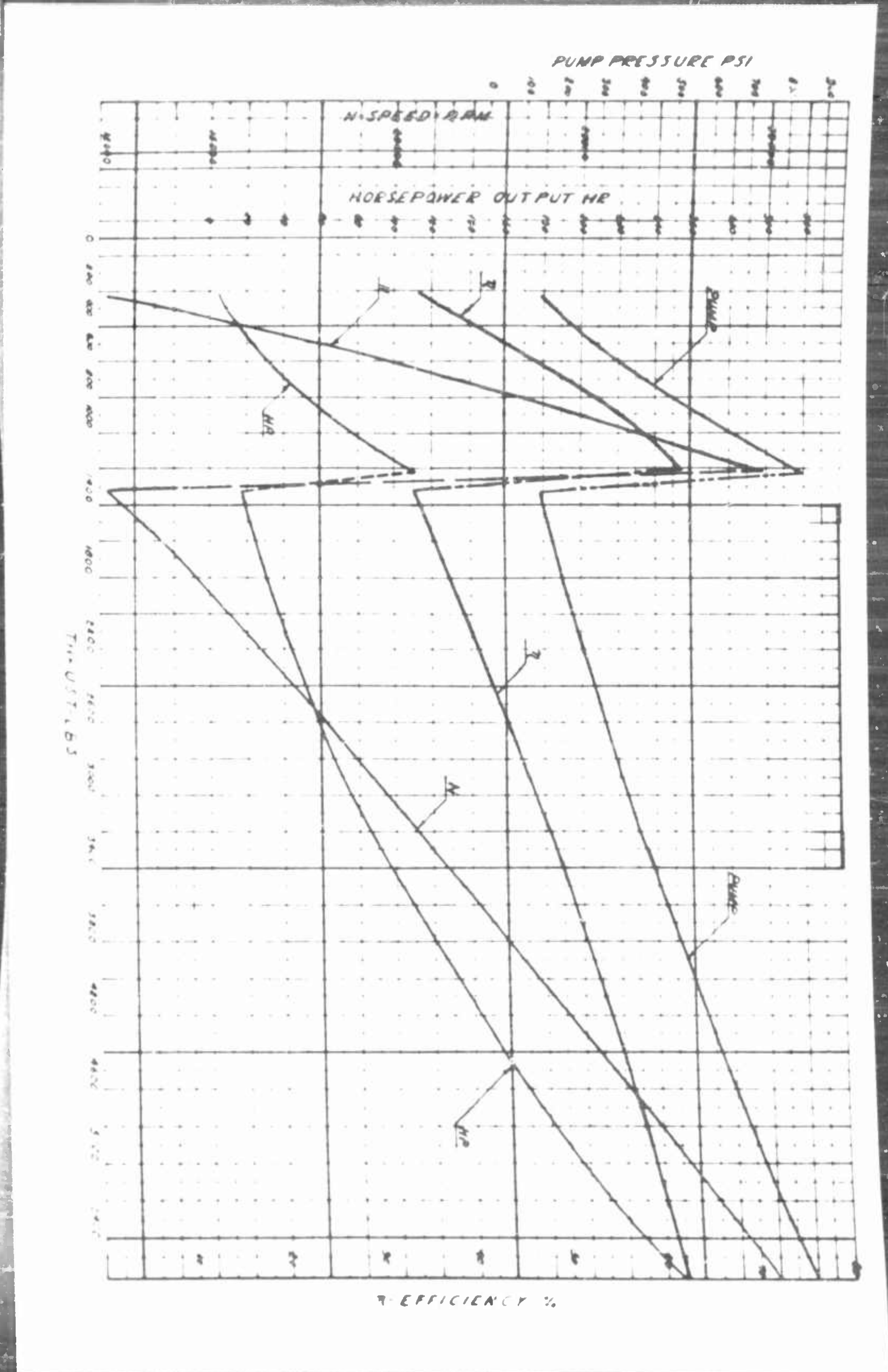


Fig. 17 - Turbine-Pump Performance - P 3390C/SK 1297

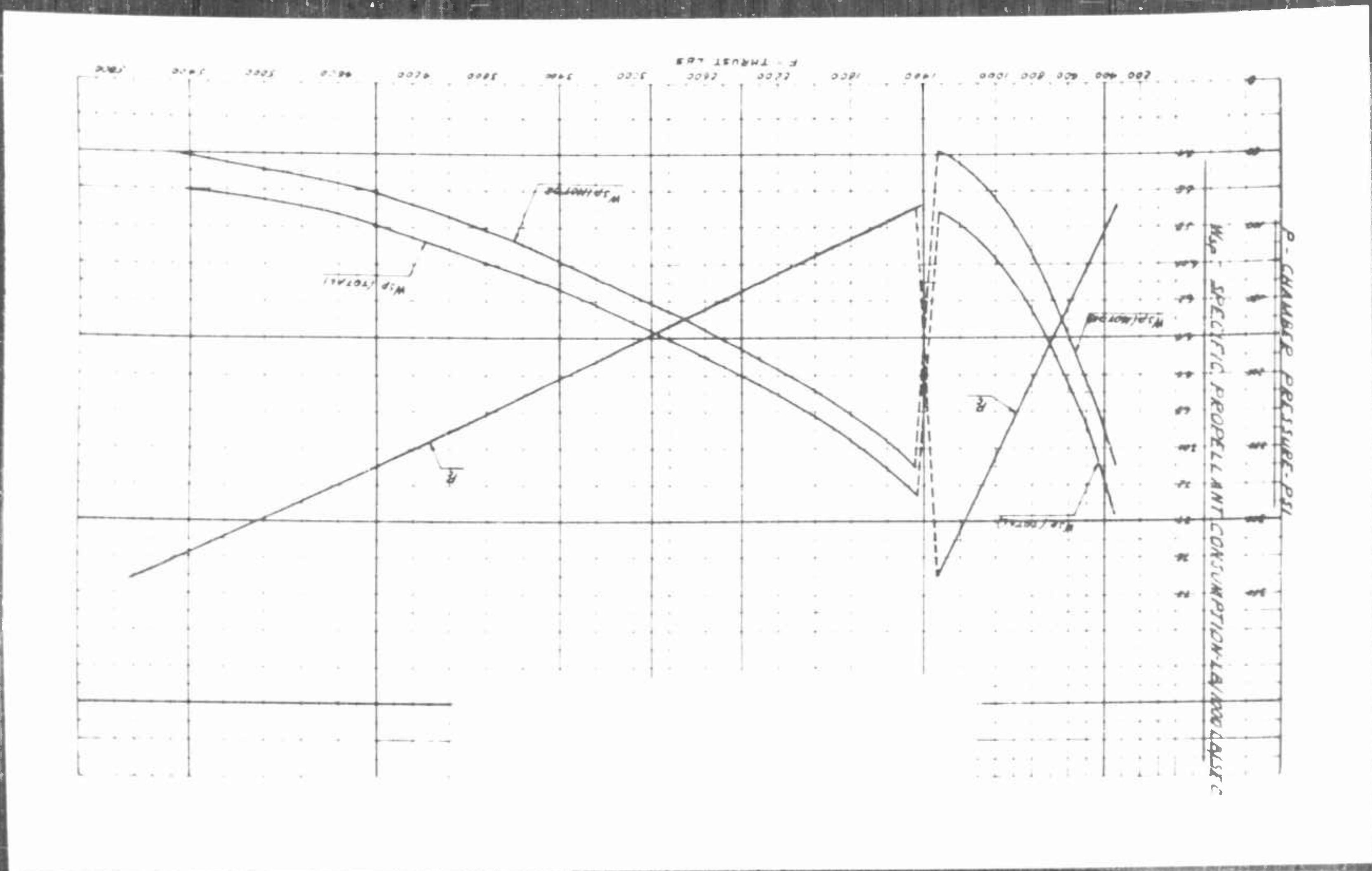


Fig. 18 - Combustion Chamber Sea Level Performance - P 3390C/SK 1297

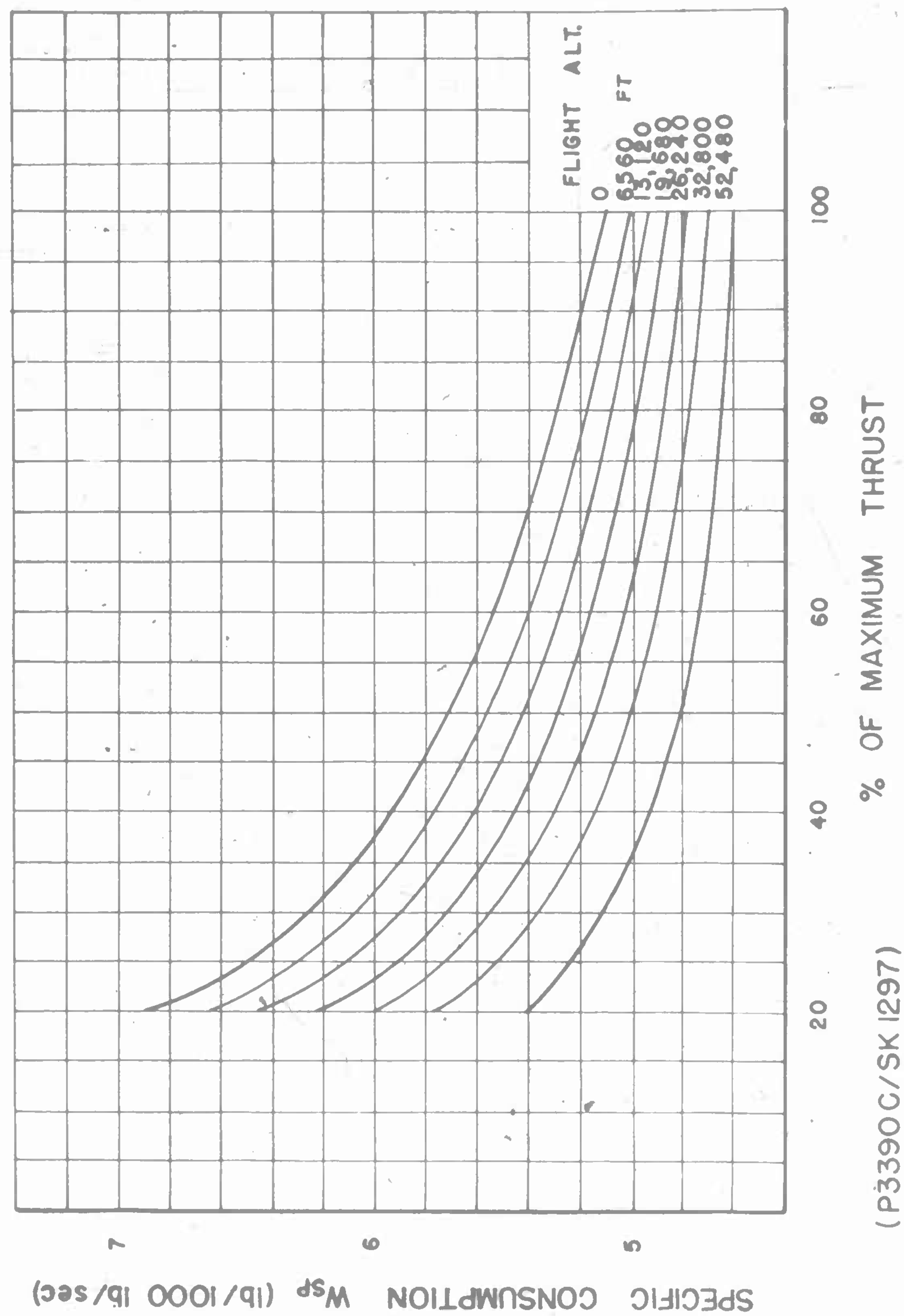


Fig. 19 - Specific Consumptions as Functions of Percentage of Maximum Thrust - P 3390C/SK 1297

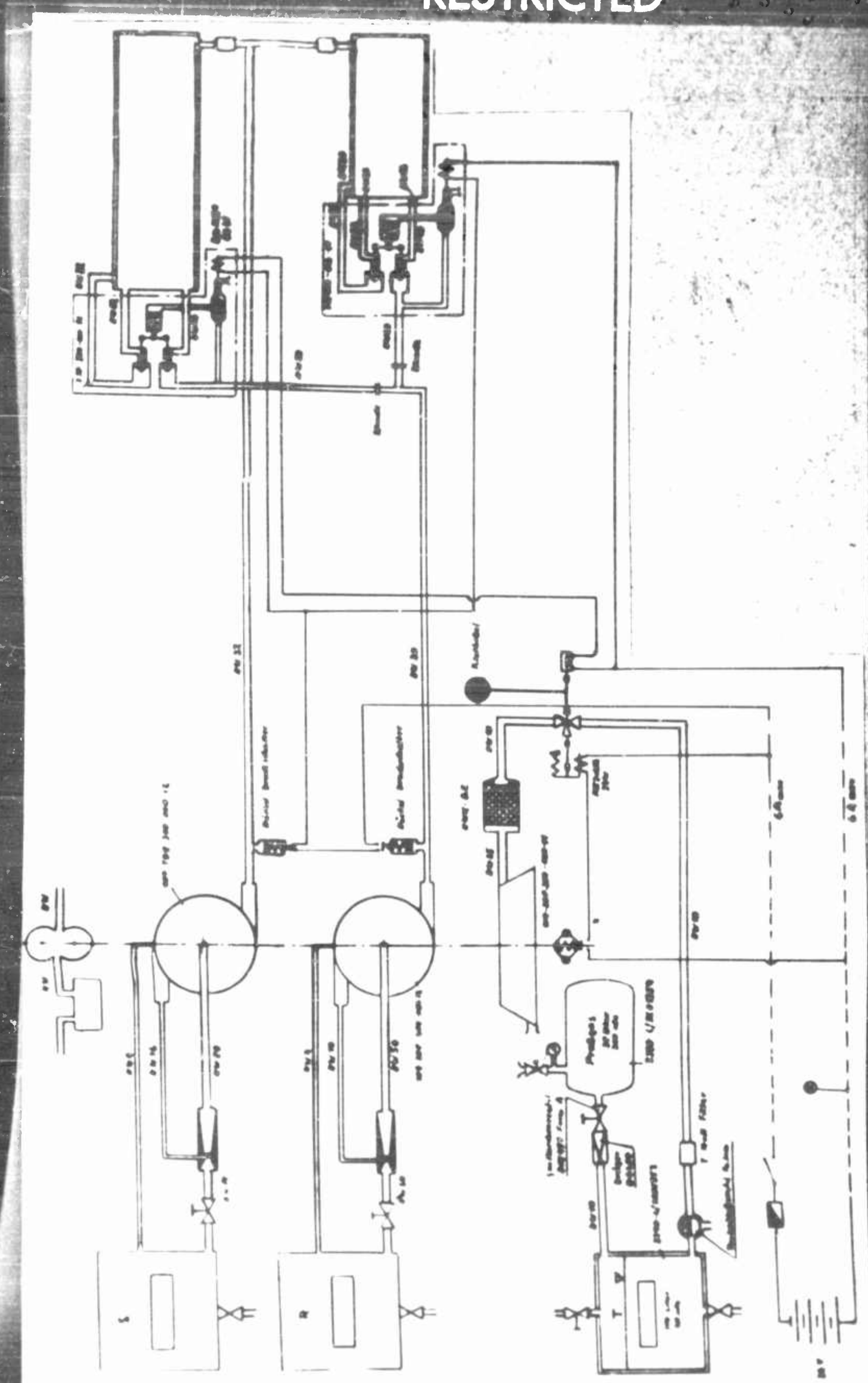


Fig. 20 - Control Schematic - 109-708B

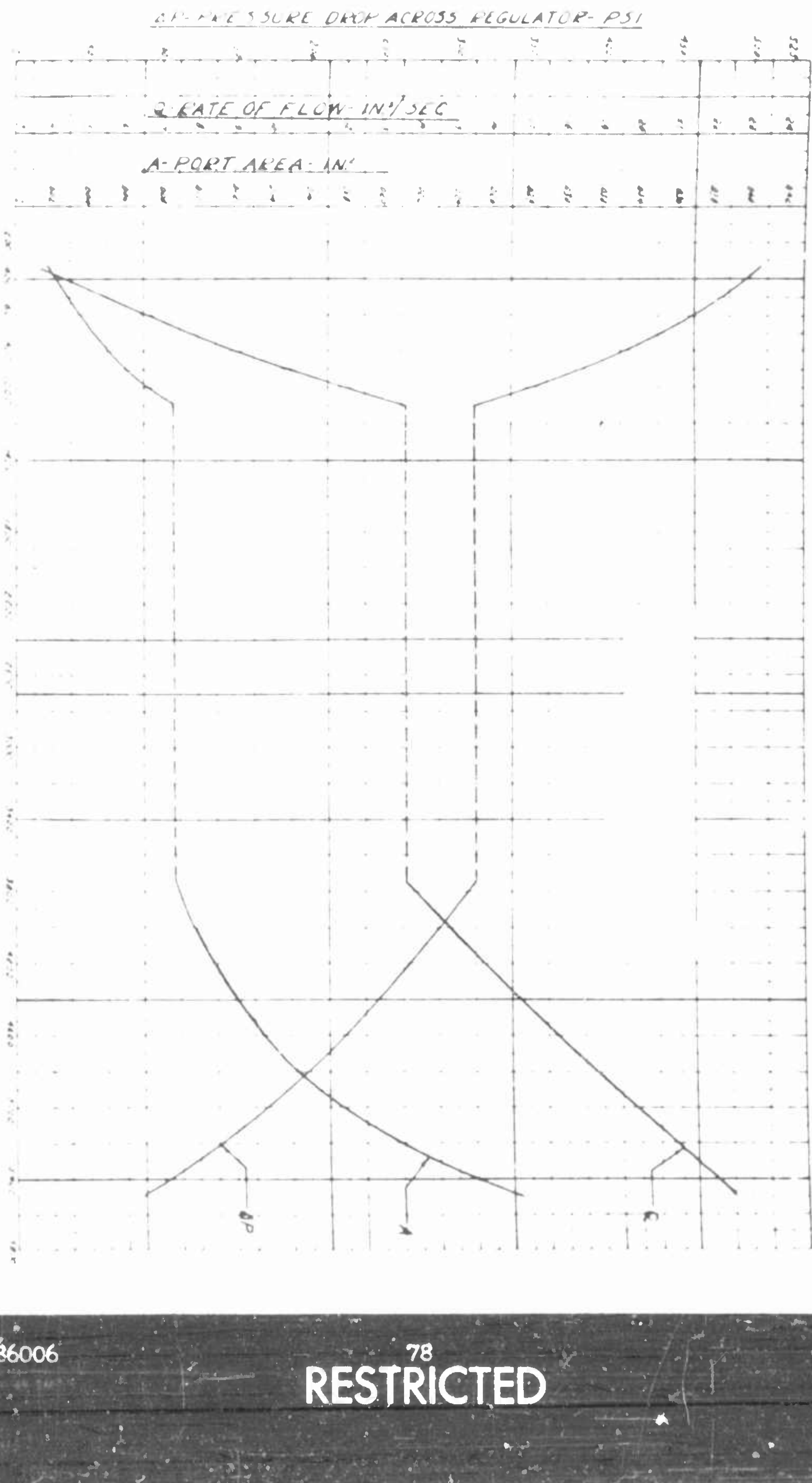


Fig. 21 - Regulator Performance - 109-708B

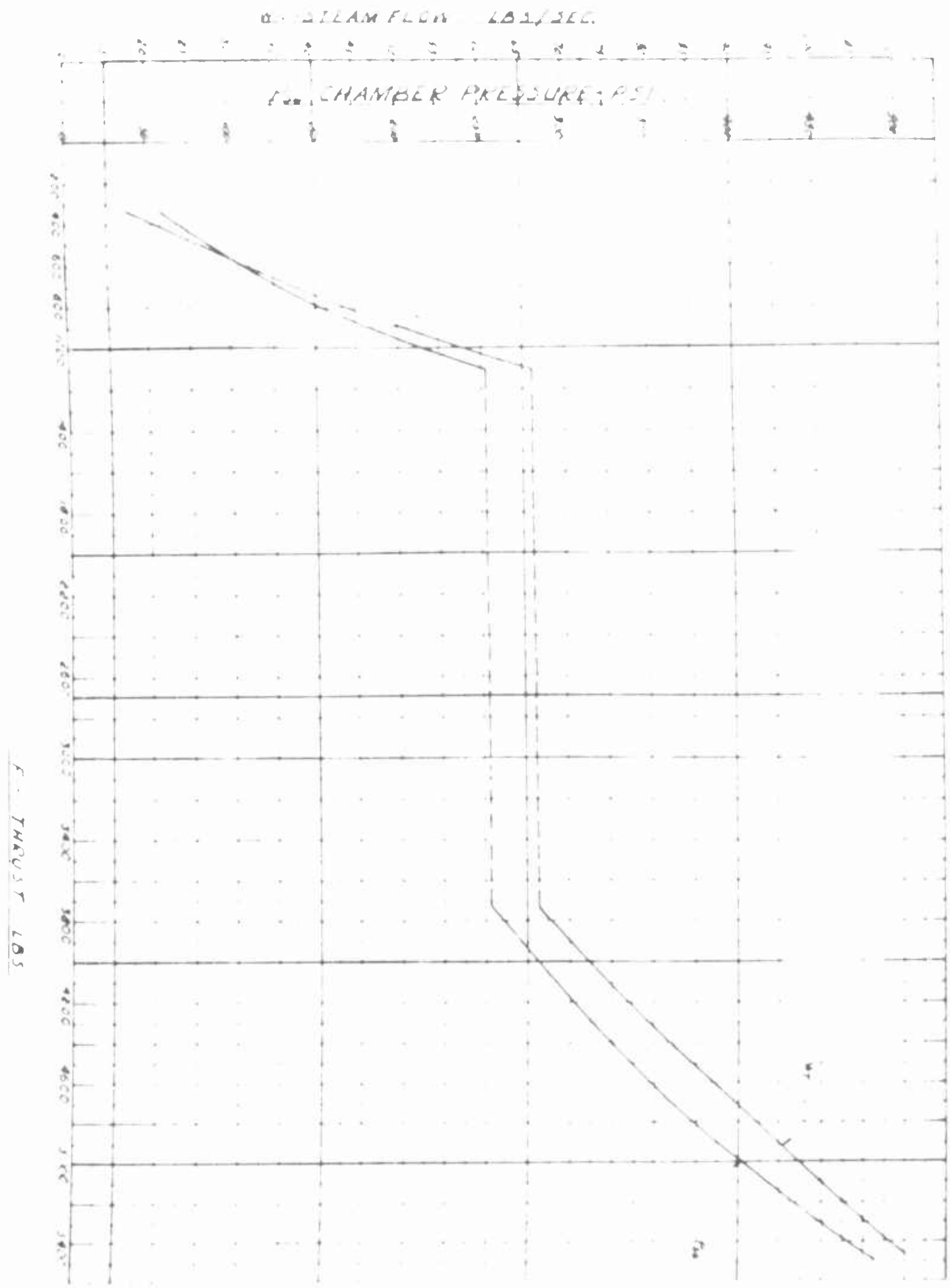


Fig. 22 - Steam Generator Performance -/109-708B

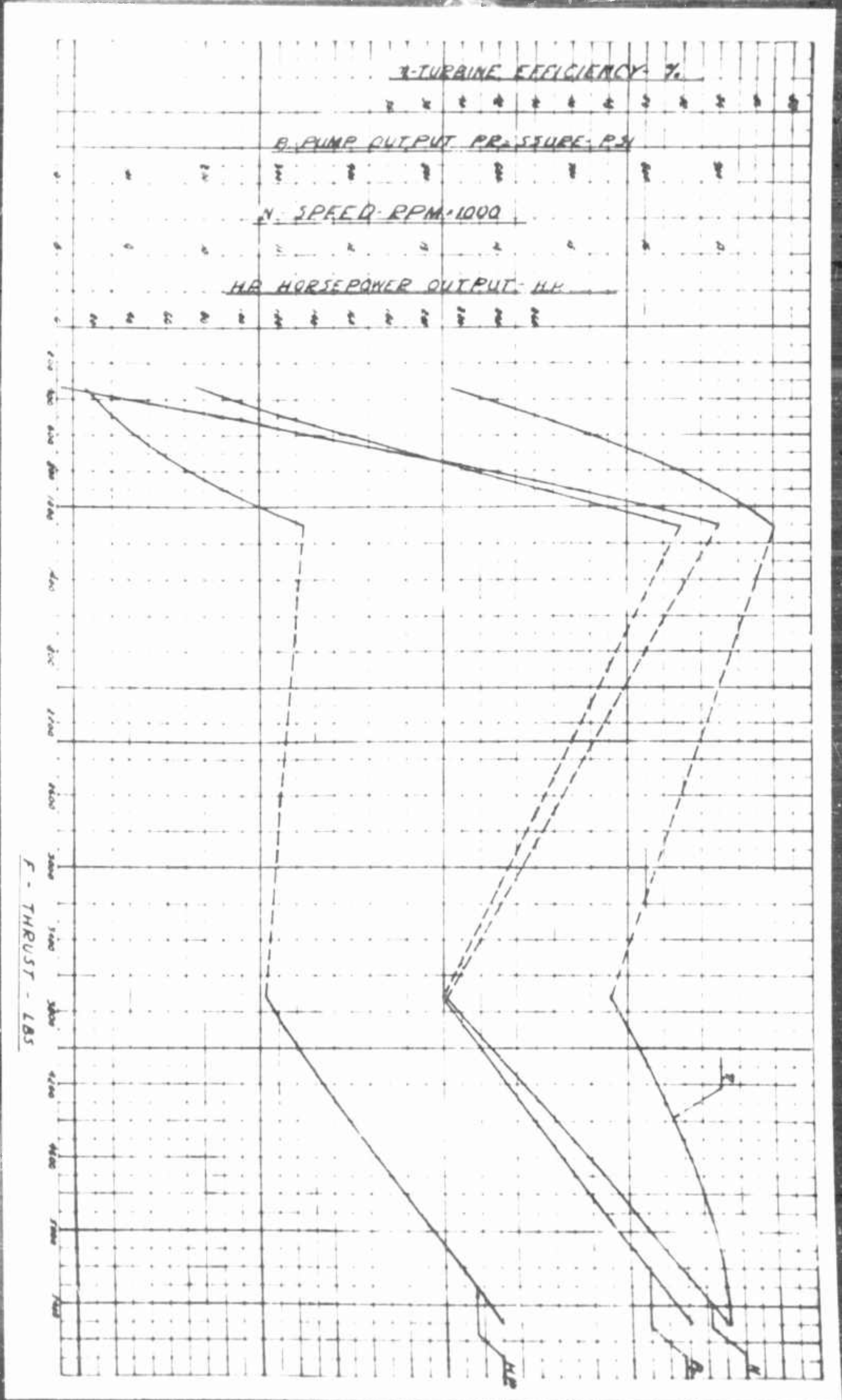


Fig. 23 - Turbine-Pump Performance - 4100-708B

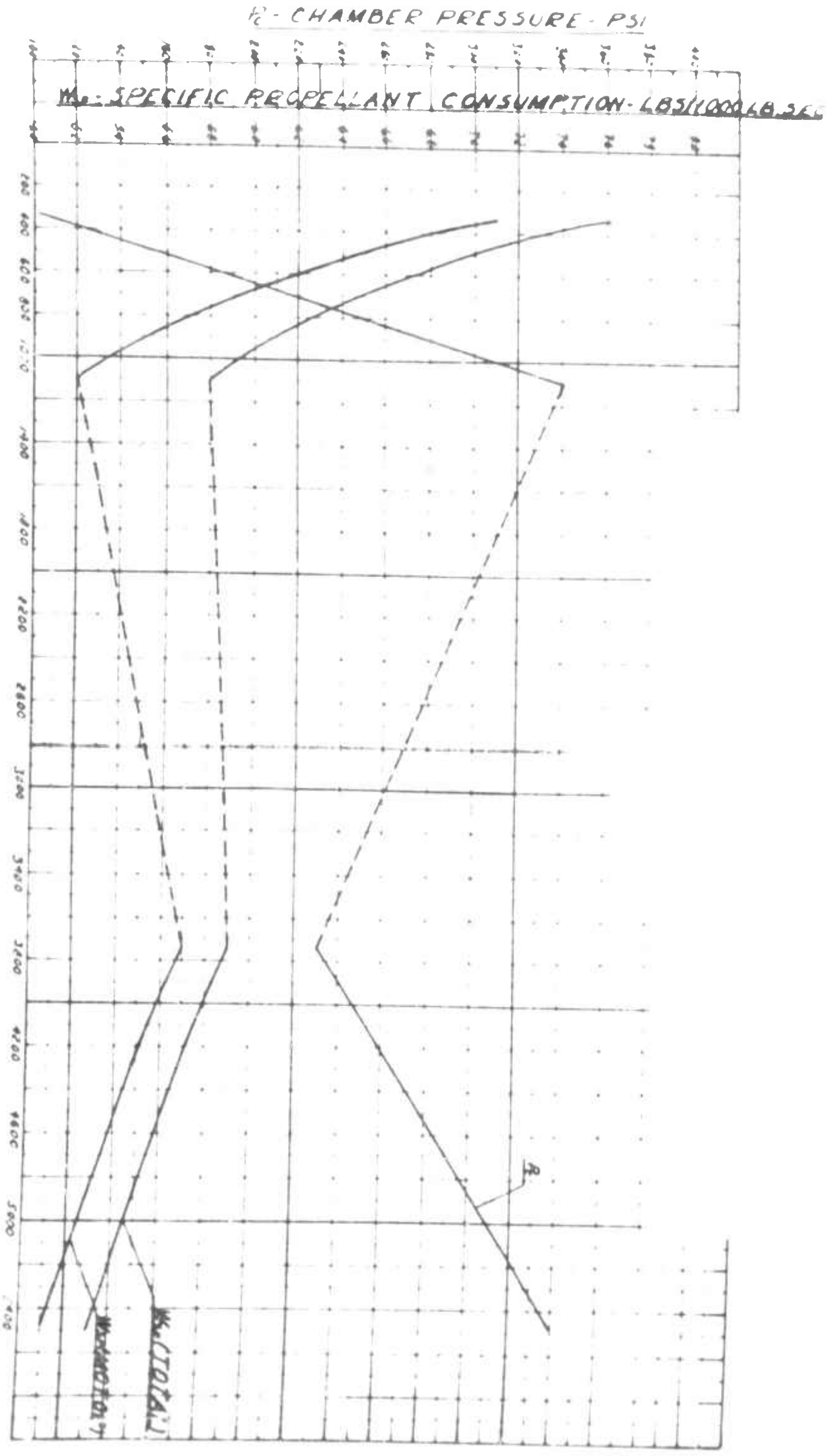


Fig. 24 - Combustion Chamber Sea Level Performance 109-708B

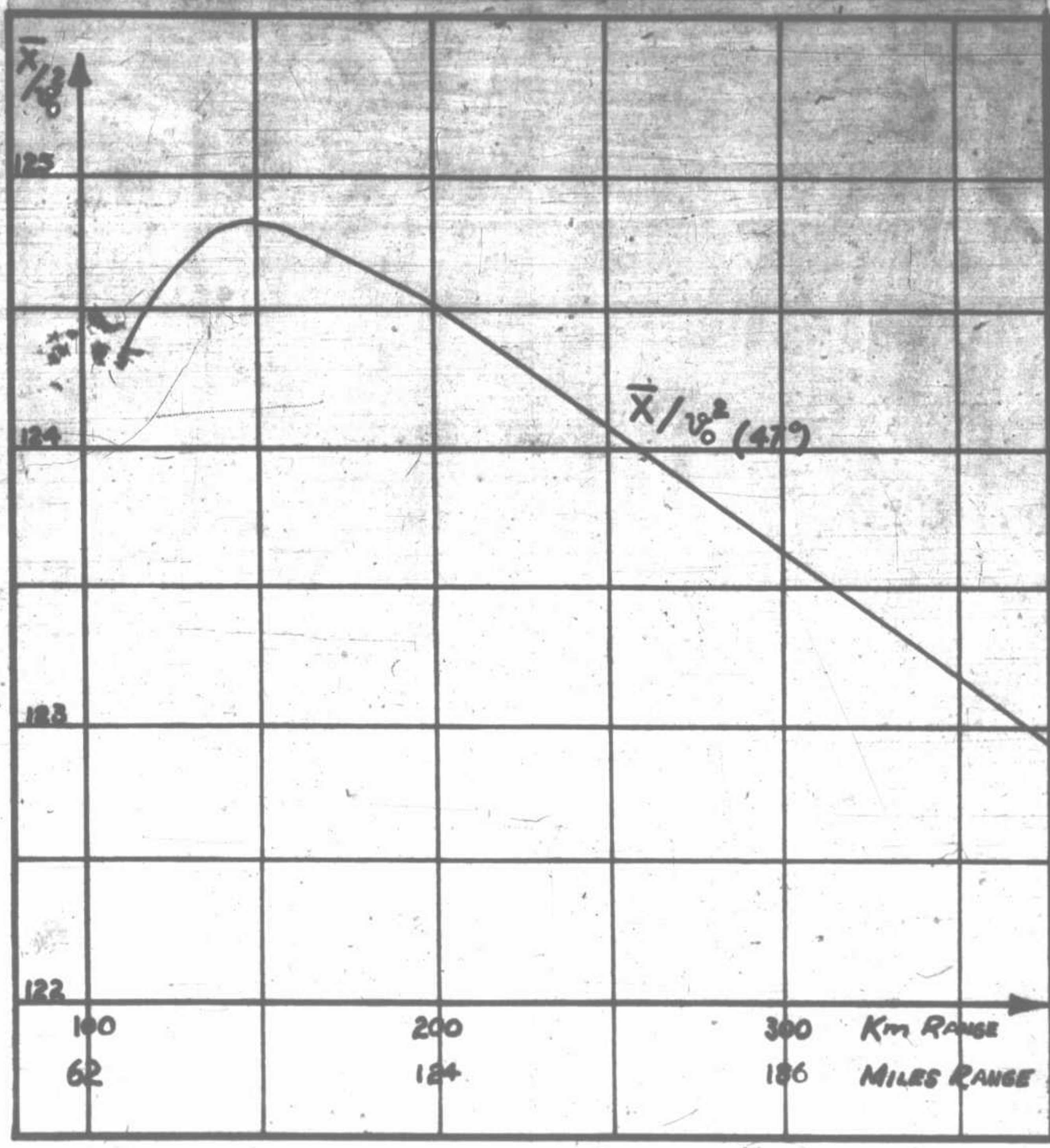


Fig. 25 - Relationship Between the Cutoff Velocity V_o and the Total Range of the Trajectory for the A-4

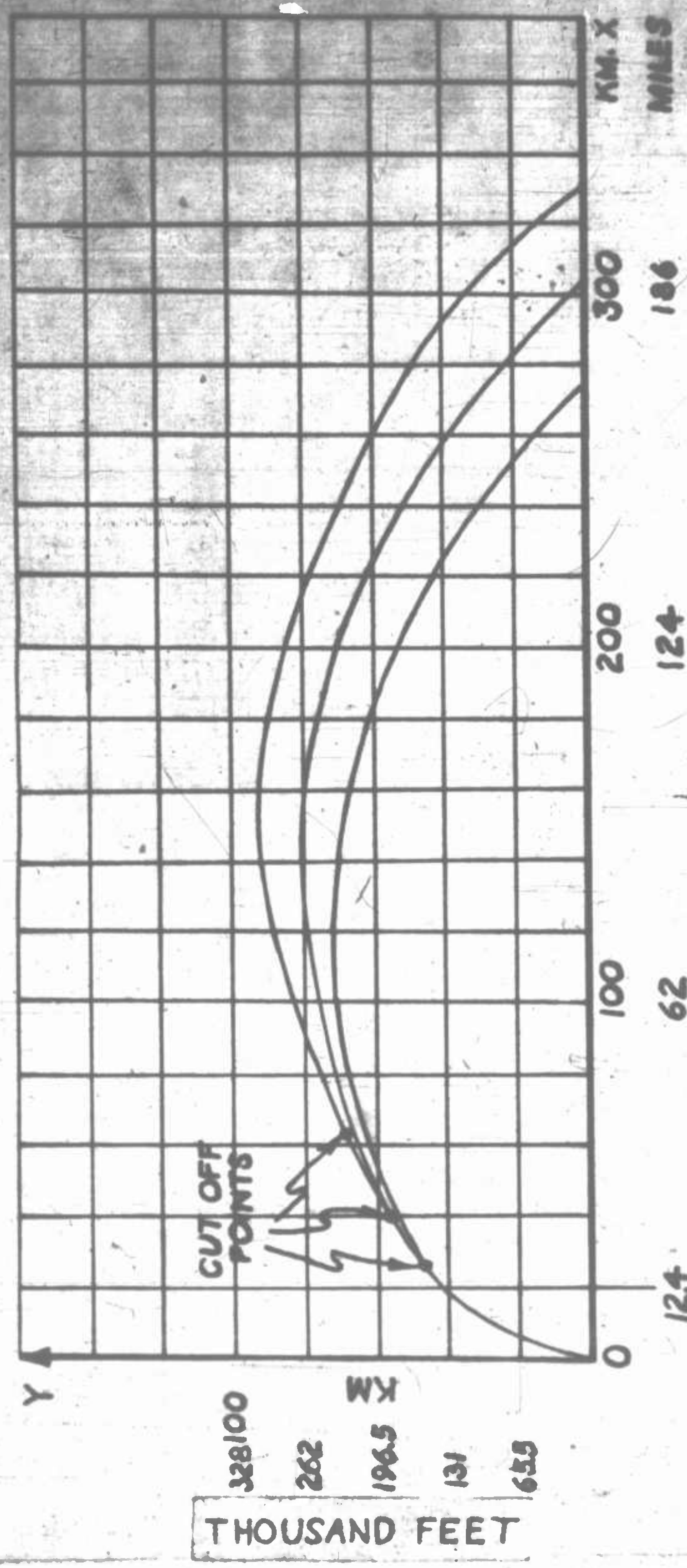


Fig. 26 - Trajectories with Same Propelled Path but Different Cutoff Velocities for the A-4

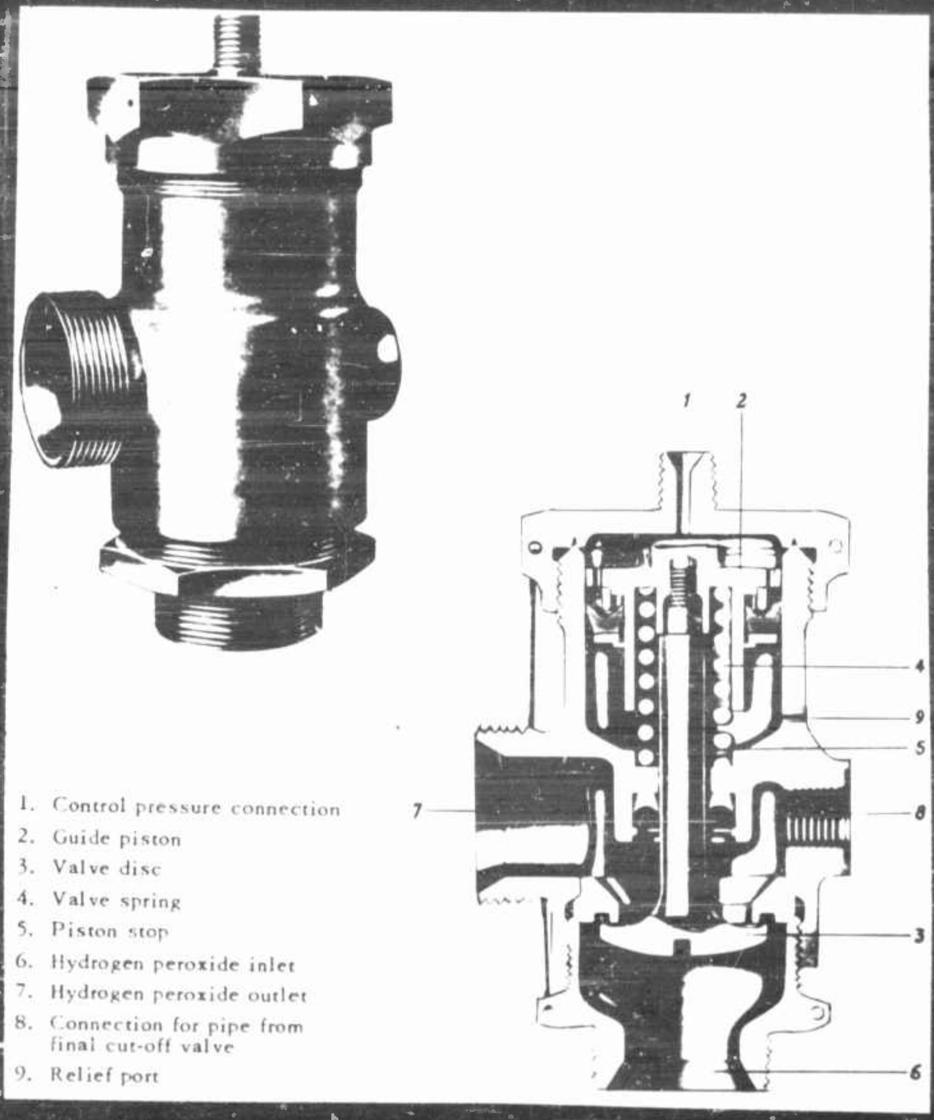
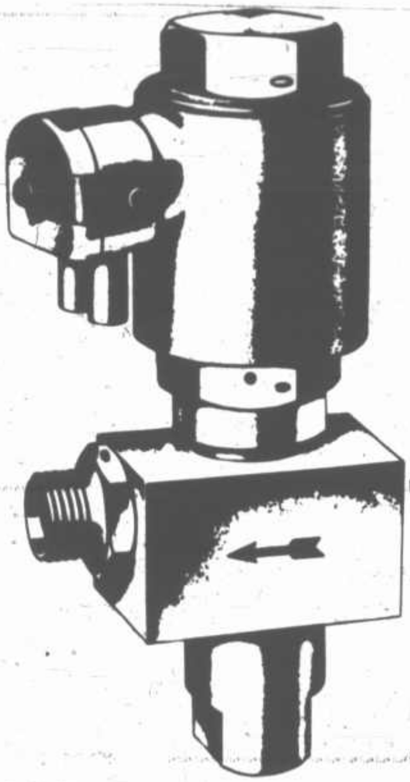
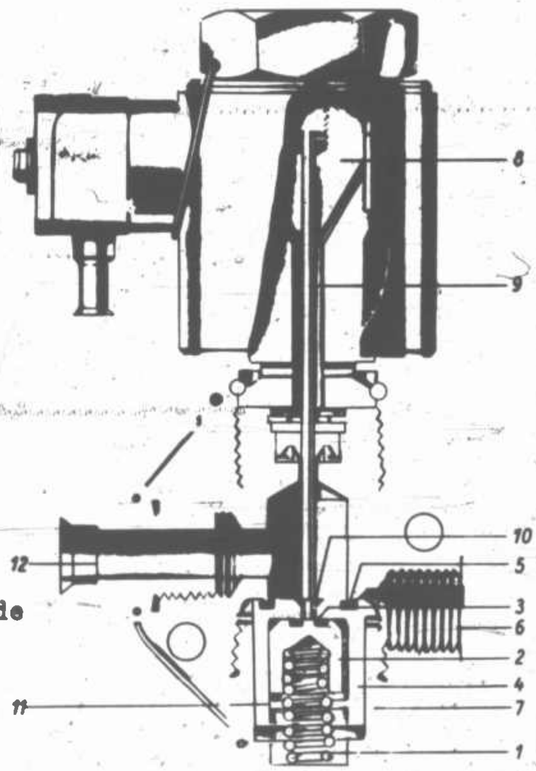


Fig. 27 - Main Peroxide Cutoff Valve - A-4





1. Compression spring
2. Auxiliary valve piston
3. Seat for 2
4. Main piston
5. Seat for 4
6. Inlet port for hydrogen peroxide
7. Body
8. Magnet core
9. Tappet
10. Orifice
11. Lock ring
12. Outlet for hydrogen peroxide to steam generator

Fig. 28 - Final Peroxide Cutoff Valve - A-4

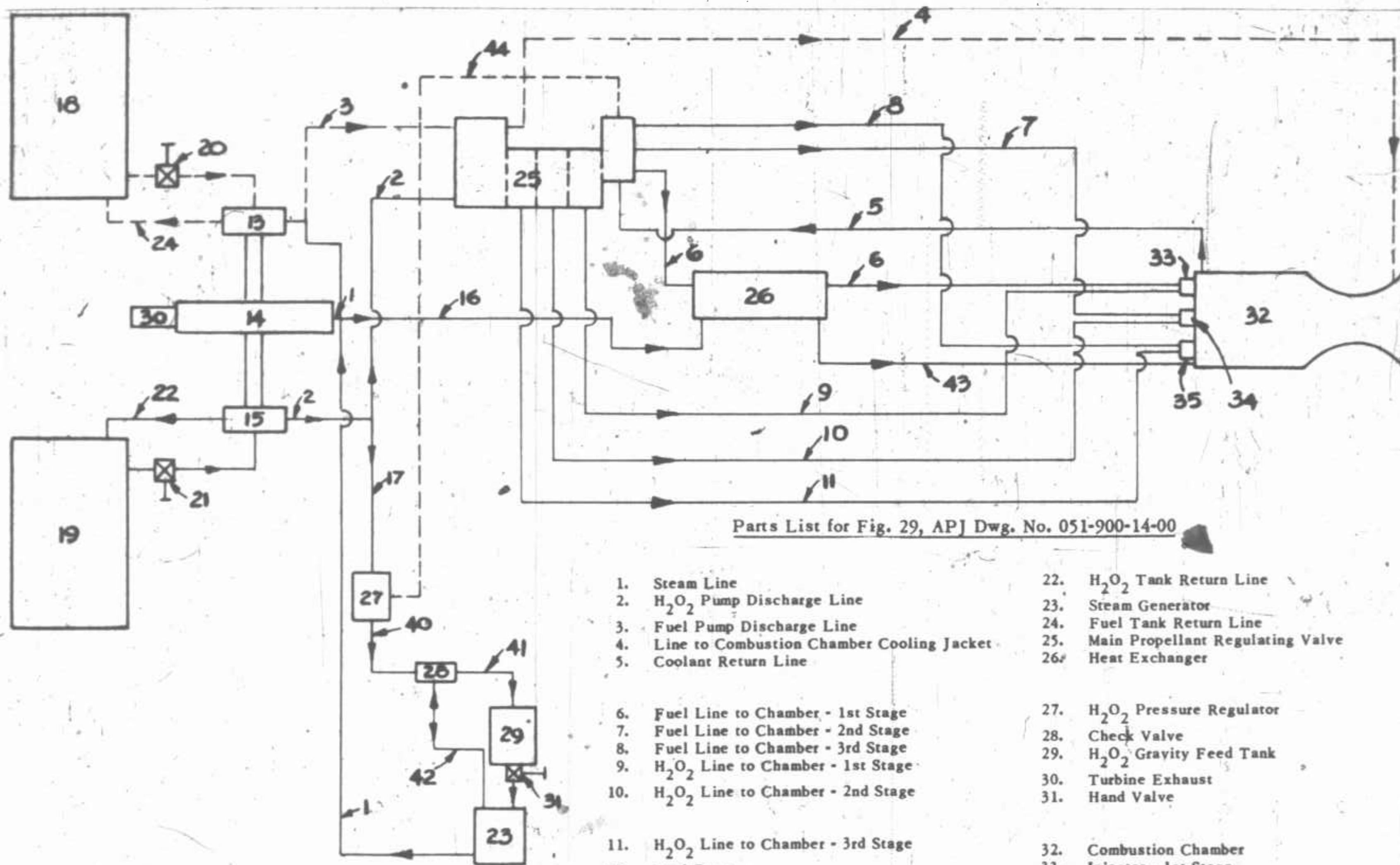


Fig. 29 - Schematic Arrangement - 109-509A-2 (APJ Drawing No. 051-900-14-00)

Parts List for Fig. 29, APJ Dwg. No. 051-900-14-00

1. Steam Line
2. H_2O_2 Pump Discharge Line
3. Fuel Pump Discharge Line
4. Line to Combustion Chamber Cooling Jacket
5. Coolant Return Line

6. Fuel Line to Chamber - 1st Stage
7. Fuel Line to Chamber - 2nd Stage
8. Fuel Line to Chamber - 3rd Stage
9. H_2O_2 Line to Chamber - 1st Stage
10. H_2O_2 Line to Chamber - 2nd Stage

11. H_2O_2 Line to Chamber - 3rd Stage
13. Fuel Pump
14. Turbine
15. H_2O_2 Pump
16. Steam Line to Heat Exchanger

17. H_2O_2 Line to Regulator
18. Fuel Tank
19. H_2O_2 Tank
20. Fuel Tank Shut-off Valve
21. H_2O_2 Tank Shut-off Valve

22. H_2O_2 Tank Return Line
23. Steam Generator
24. Fuel Tank Return Line
25. Main Propellant Regulating Valve
26. Heat Exchanger

27. H_2O_2 Pressure Regulator
28. Check Valve
29. H_2O_2 Gravity Feed Tank
30. Turbine Exhaust
31. Hand Valve

32. Combustion Chamber
33. Injector - 1st Stage
34. Injector - 2nd Stage
35. Injector - 3rd Stage
40. H_2O_2 Regulator Line

41. H_2O_2 Gravity Tank Refill Line
42. Steam Generator Feed Line
43. Heat Exchanger Vent Line
44. Mechanical Linkage

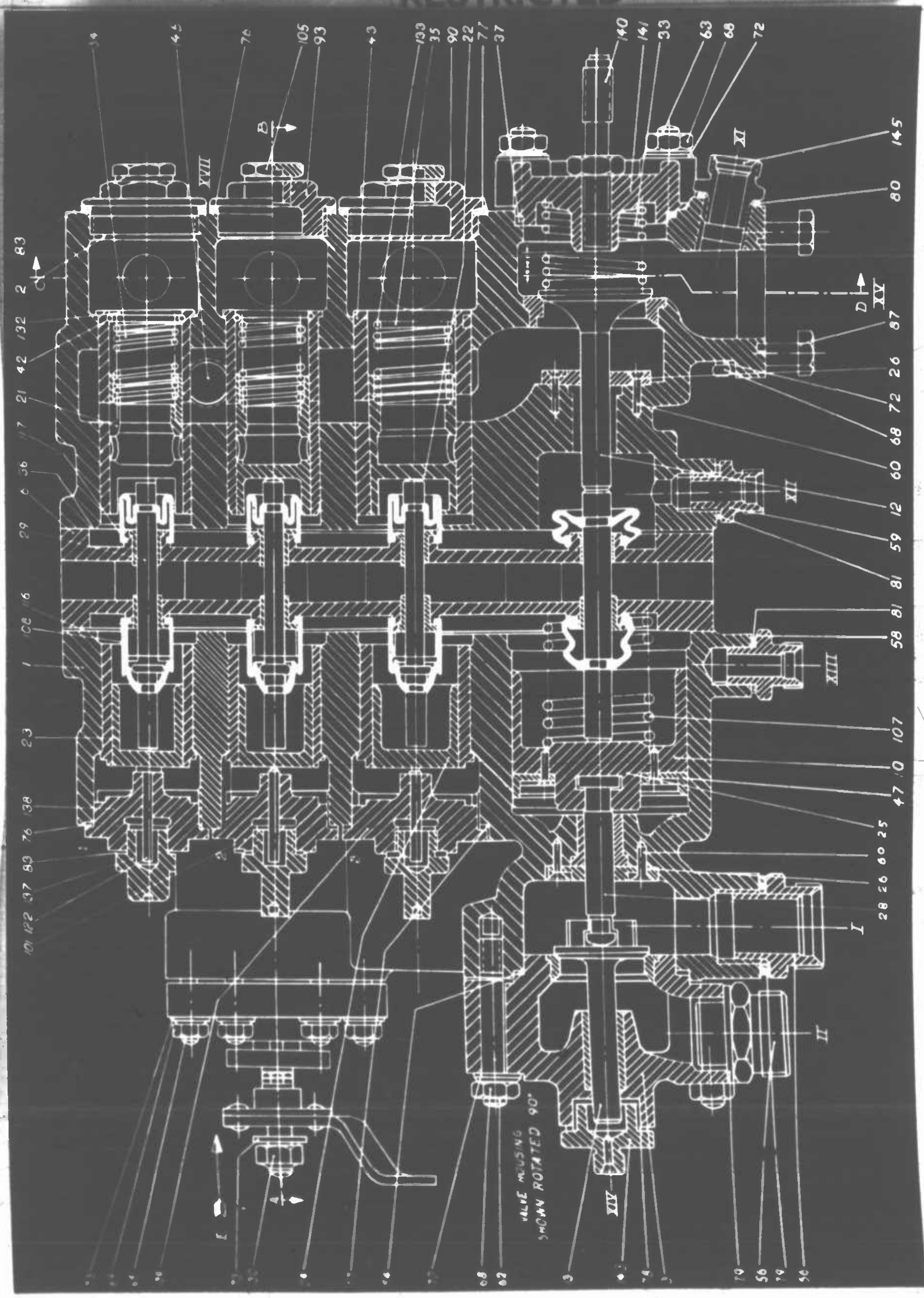


Fig. 30 - Regulator Assembly - German Drawing No. 109-509.381-000.10
(API Drawing No. D-5-509-8) - (Sheet 1 of 4 sheets)

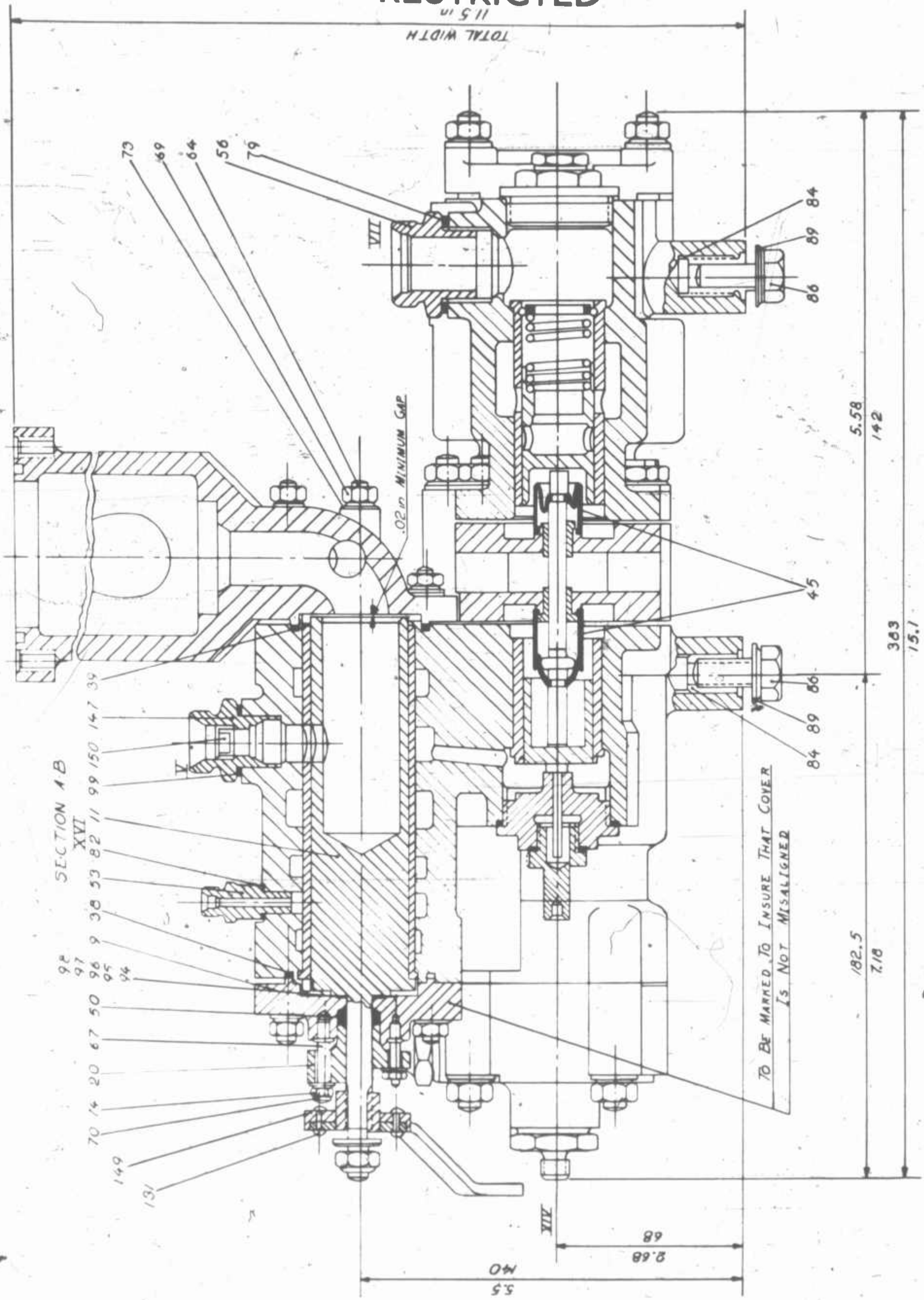
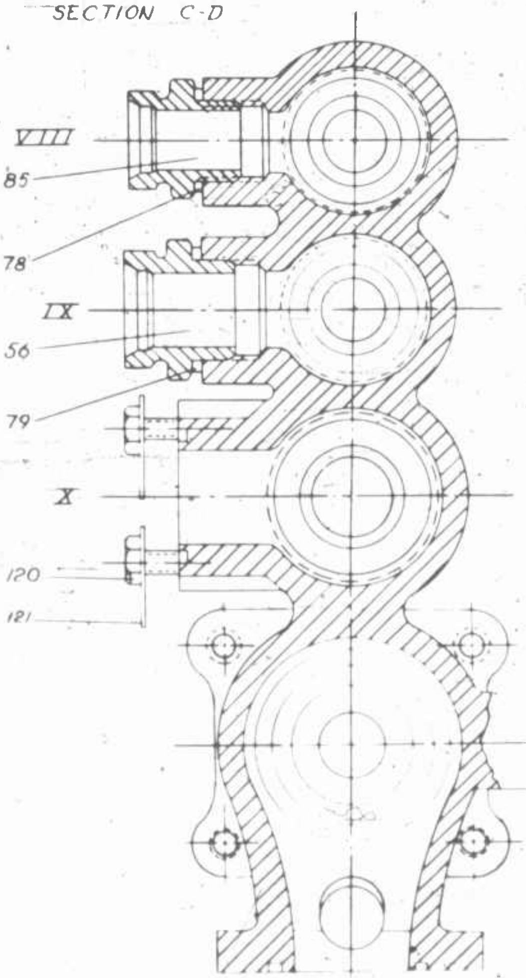
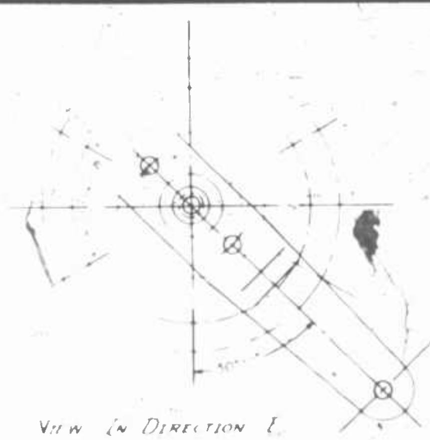


Fig. 30 - (Sheet 2 of 4 sheets)

149	109-509.611-019.14	150	109-509.301-126.14	151	109-509.301-127.14		
145	B 10 DIN 7627	146	109-509.301-125.14	147	109-509.301-121.14	148	109-509.301-122.14
141	109-509.301-120.14	142	A 10x14 DIN 7603	143	109-509.301-123.14	144	109-509.301-124.14
137	109-509.301-116.14	138	109-509.301-117.14	139	109-509.301-118.14	140	109-509.301-119.14
133	109-509.301-112.14	134		135		136	
129		130	M6 AGGN 14487.2	131	6x15 DIN L 71	132	109-509.301.111.14
125		126		127		128	
121	6.4 DIN 93	122	109-509.301-103.14	123		124	
117	109.509.301-098.1	118		119		120	M6x26 DIN 933
113		114		115		116	109-509.301-097.13
109		110		111		112	
105	BM14x1.5DIN 7604	106		107	109-509.301-088.14	108	109-509.301-089.14
101	109-509-301-087.14	102		103		104	
97	109-509.301-085.14	98	109-509.301-086.14	99	A 18x22 DIN 7603	100	
93	109-509.301-081.14	94	109-509.301-082.14	95	109-509.301-083.14	96	109-509.301-084.14
89	10.3 DIN 125	90	109-509.301-079.14	91		92	
85	B 16 DIN 7627	86	M10x25SK DIN 933	87	M8x52 DIN 931	88	
81	A 14x18 DIN 7603	82	A8x12 DIN 7603	83	A14x20 DIN 7603	84	M10x20 LgN 14461
77	45x32 DIN 7605	78	A22x27 DIN 7603	79	A26x32 DIN 7603	80	A 16 x 20 DIN 7605
73	6.4 DIN 125	74	4.3 DIN 125	75		76	38x44 DIN 7603
69	M6 AGGN 14487.2	70	M4 AGGN 14487.2	71		72	8.4 DIN 125
65	M6x24LgN 14156.1	66	M6x22LgN 14156.1	67	M4x10LgN 14156.1	68	M8 AGGN 14487.2
61	M8x62LgN 14156.1	62	M8x46LgN 14156.1	63	M8x50LgN 14156.1	64	M6x52LgN 14156.1
57		58	B 10 DIN 7627	59	B 8 DIN 7627	60	M3x10 DIN 88
53	109-509.301-078.14	54	A 32x60 DIN 7603	55		56	B 20 DIN 7627
49	H 10-1	50	109-509.301-049.1	51	109-509.301-076.14	52	
45	109-509.301-073.14	46	109-509.300-074.14	47	T 60-1	48	H 10-1
41		42	109-509.301-067.14	43	109-509.301-068.14	44	
37	109-509.301-062.1	38	109-509.301-063.1	39	109-509.301-064.1	40	
33	109-509.300-059.14	34	109-509.301-059.14	35	109-509.301-060.14	36	109-509.301-061.13
29	109-509.301-053.14	30	109-509.301-056.14	31		32	
25	109-509.300-050.14	26	109-509.301-051.14	27		28	109-509.301-054.14
21	109-509.301-045.13	22	109-509.301-046.13	23	109-509.301-047.14	24	109-509.301-068.16
17		18		19	109-509.300-043.14	20	109-509.300-044.14
13	109-509.301-037.14	14		15		16	
9	109-509.301-035.14	10	109-509.301-034.14	11	109-509.301-035.12	12	109-509.300-036.14
5		6	109-509.301-705.13	7		8	
1	109-509.301-700.12	2	109-509.301-701.13	3	109-509.301-702.14	4	

SECTION C-D





View in Direction I. Valve Part II is turned to the left, up to the stop

Fig. 30 - (Sheet 3 of 4 sheets)

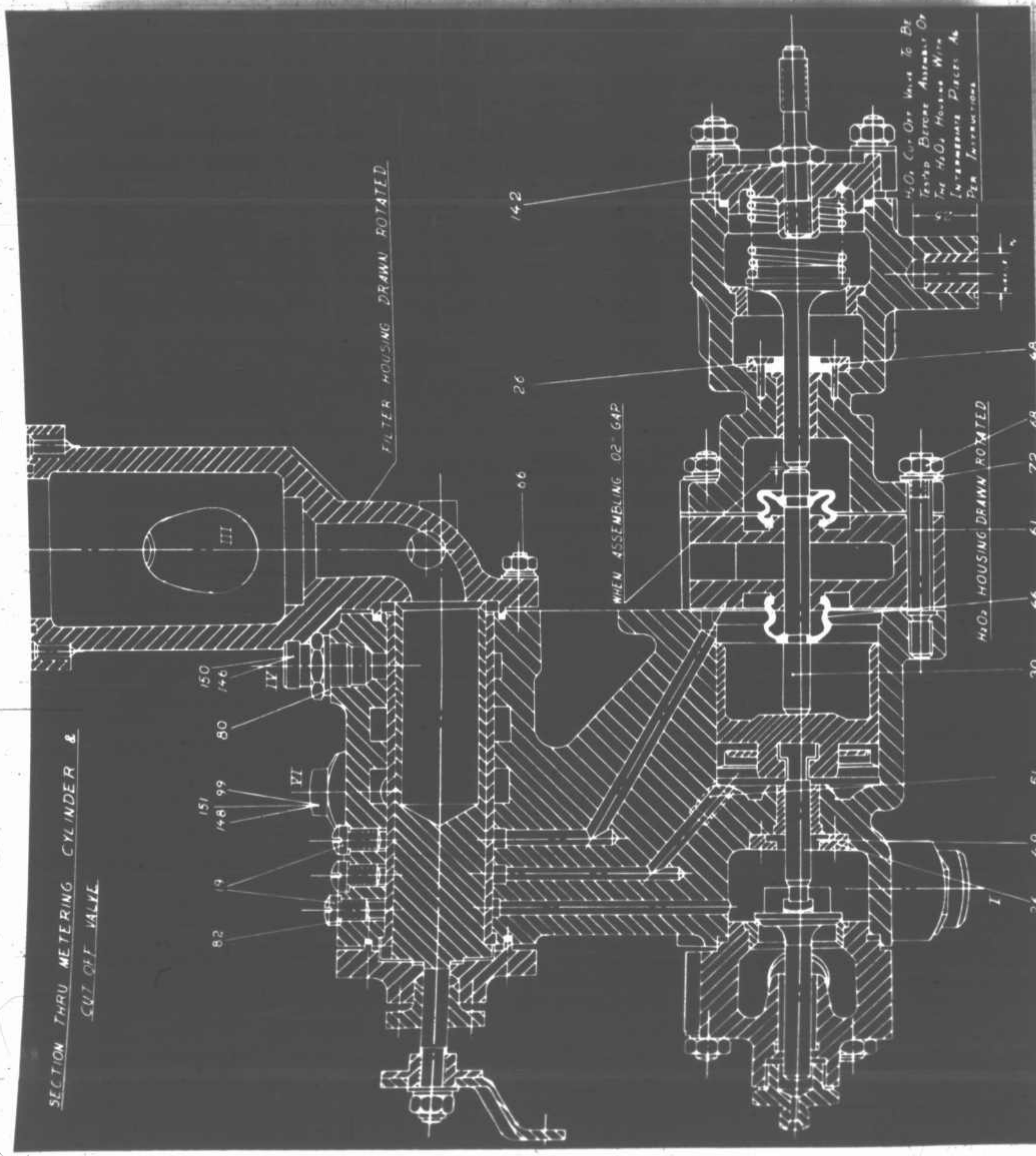


Fig. 30 - (Sheet 4 of 4 sheets)

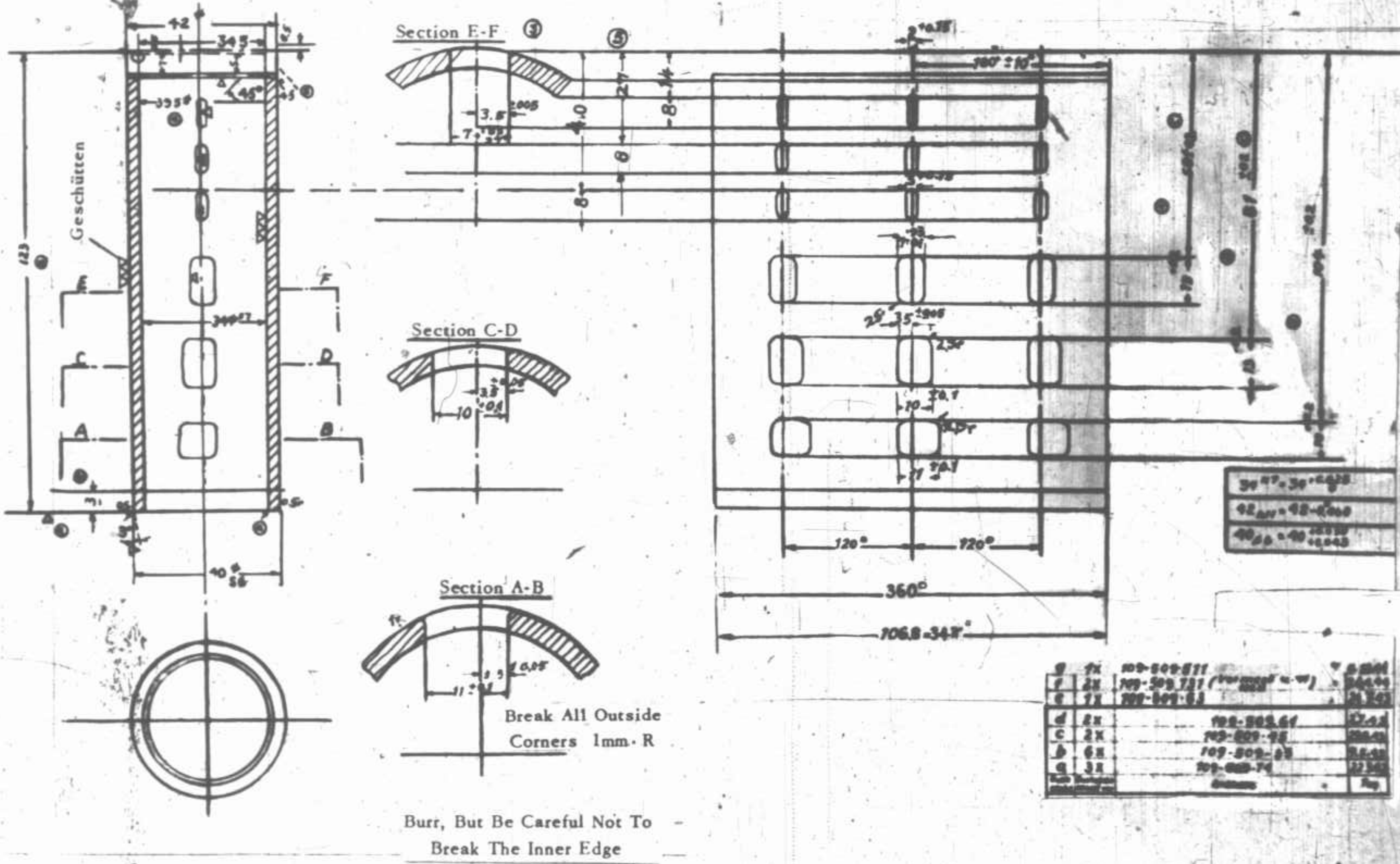


Fig. 31 - Development of the Inner Surface of the Metering Cylinder Seen From Outside - German Drawing No. 109-509.381-002.13 (APJ Drawing No. D-5-509-4)

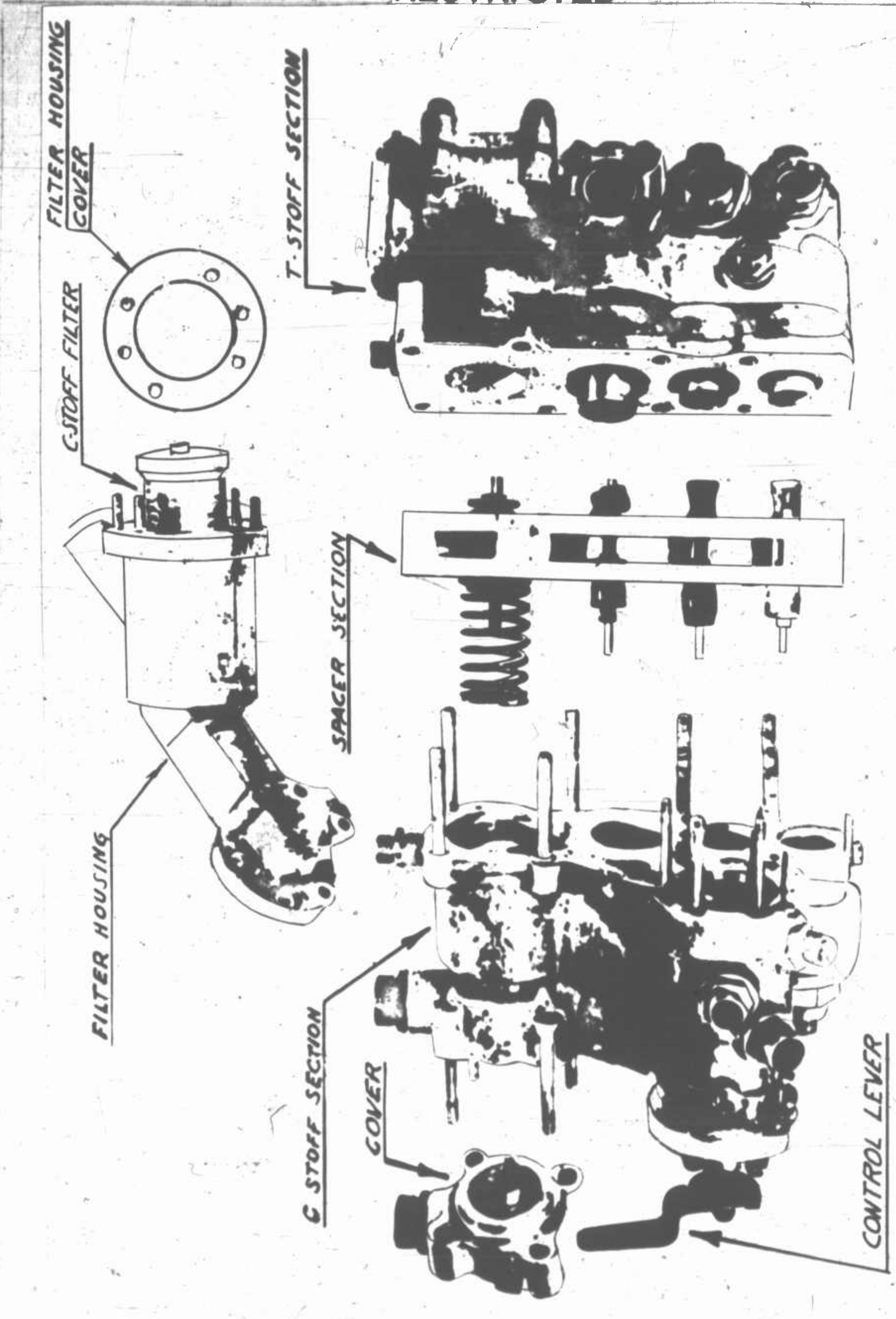


Fig. 33 - Exploded View of Regulator Valve Assembly

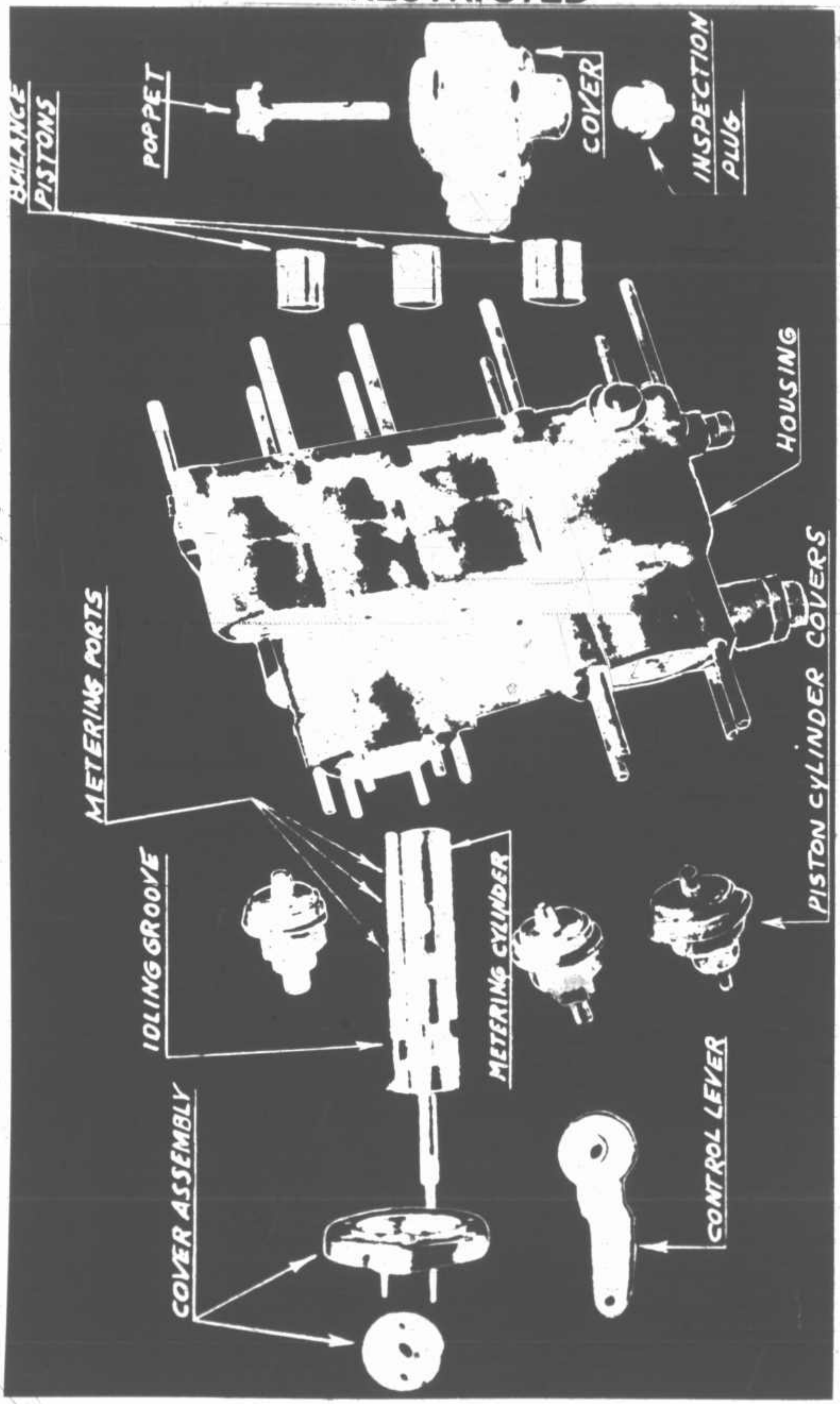


Fig. 34 - C-Stoff Section - Regulator Valve

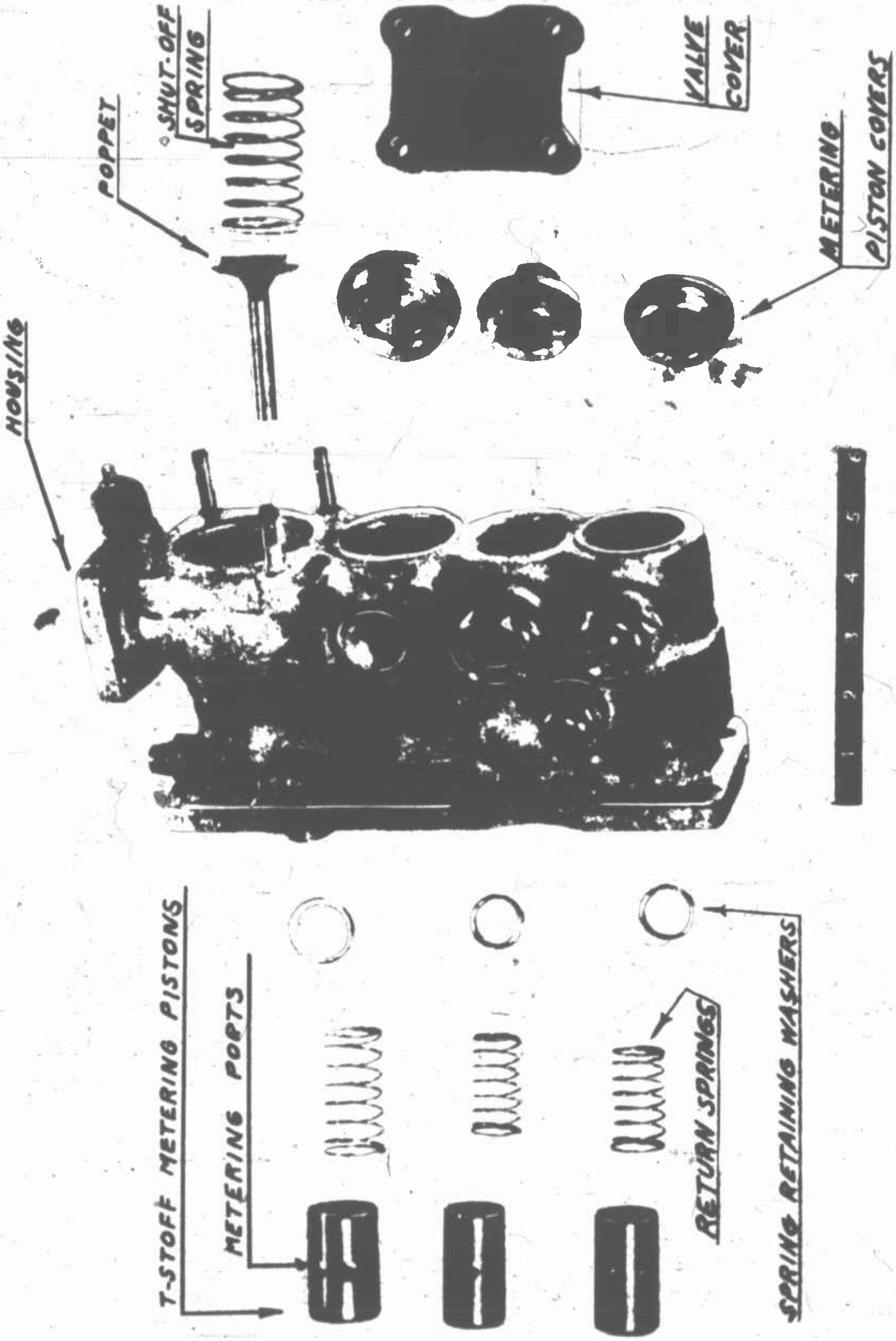
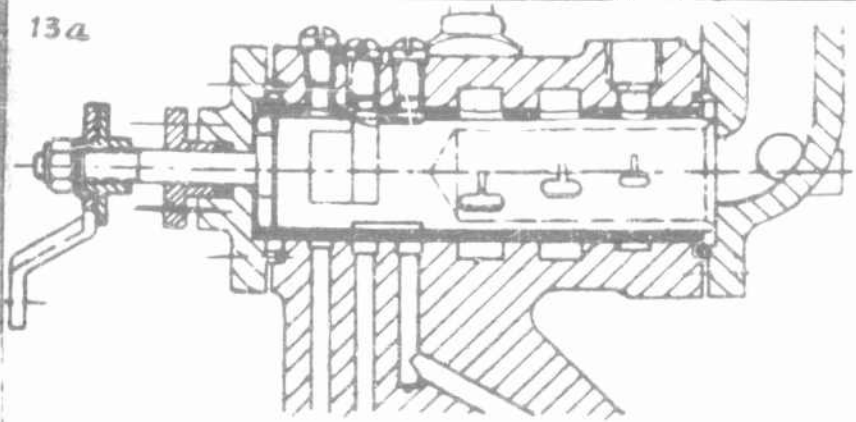


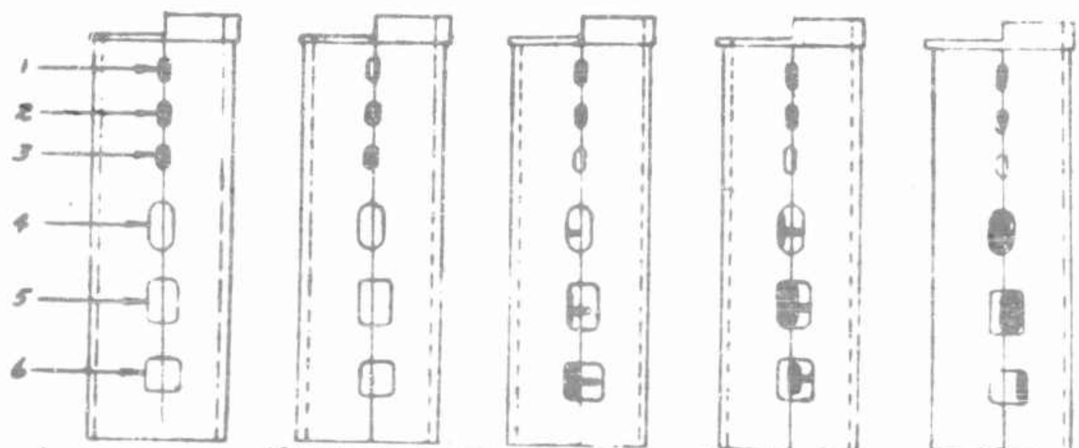
Fig. 35 - T-Stoff Section - Regulator Valve

13a



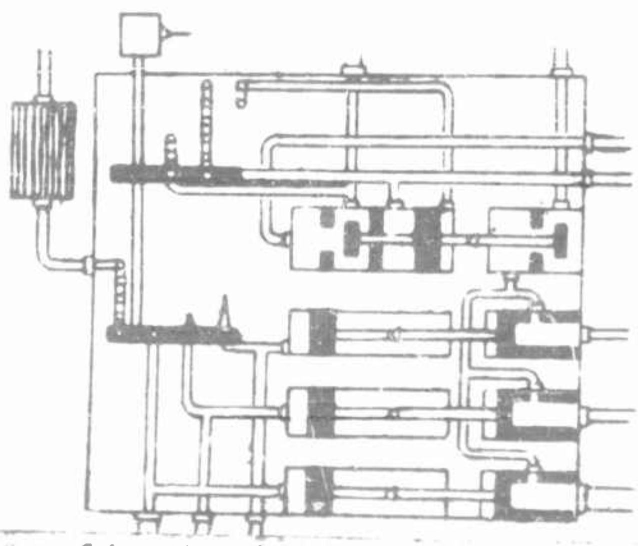
C-Stoff Metering Valve

32a



Alignment of Valve and Sleeve Ports

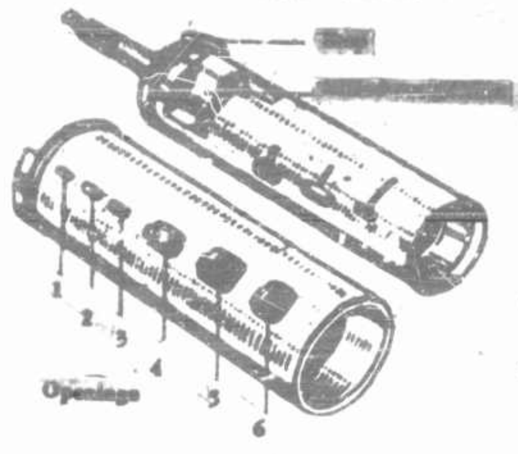
32b



Schematic - Full Thrust Position

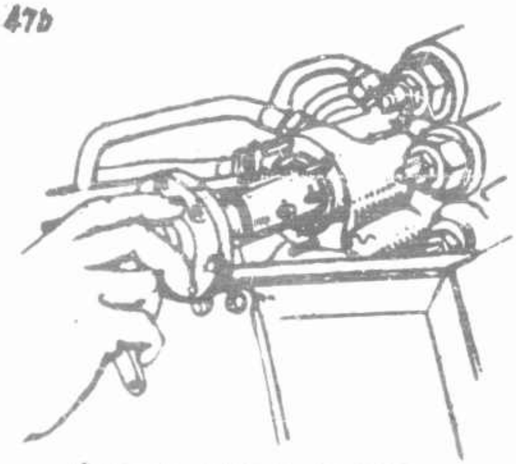
[illegible] Views [illegible] and [illegible]

.13b [redacted]



.47a [redacted]

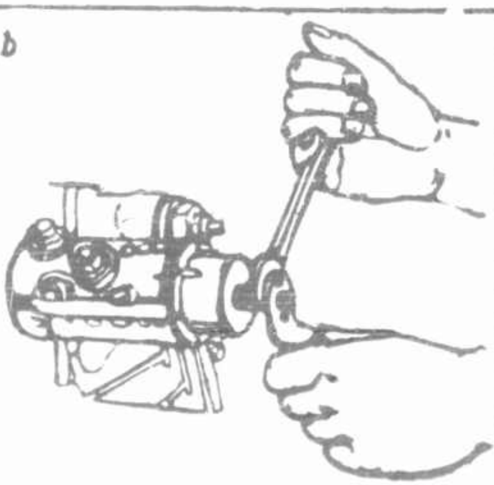
47b



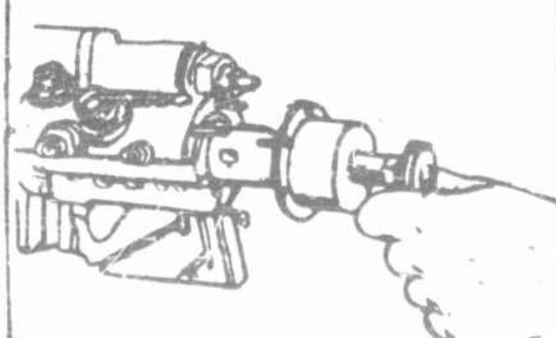
Removal of control valve

.52a [redacted]

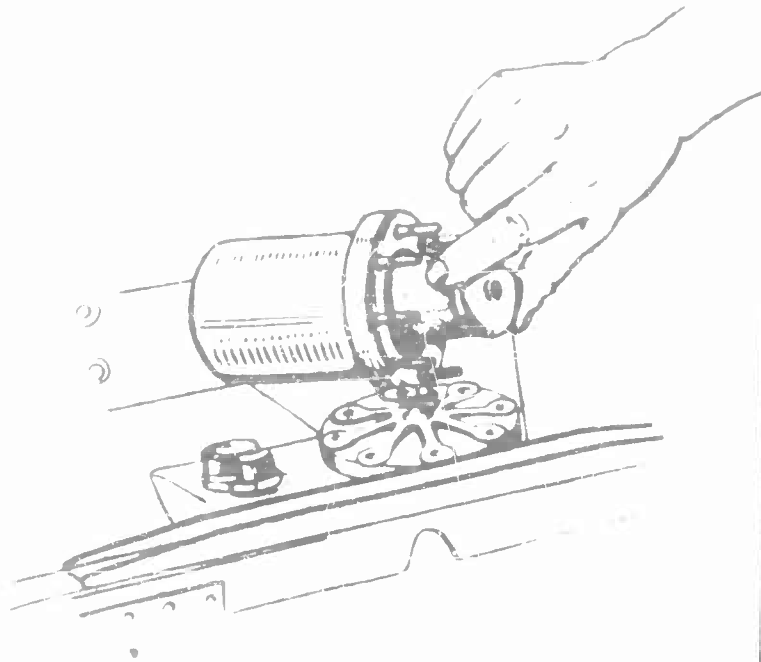
52b



.52c

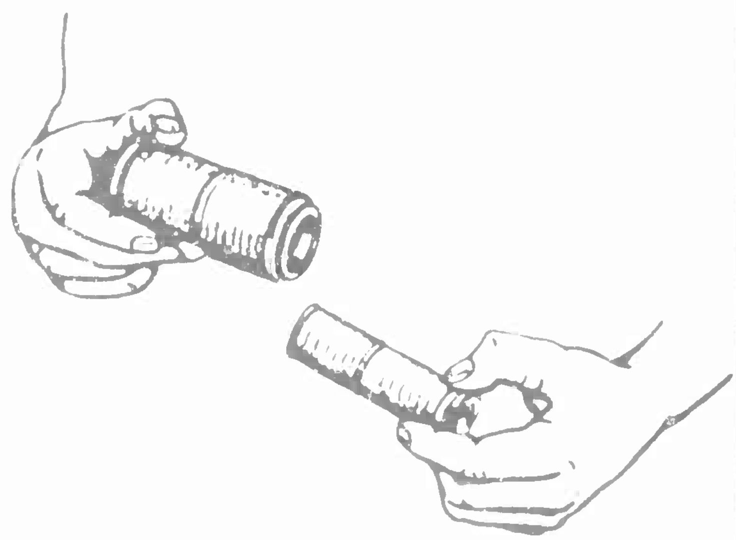


Disassembly of rotary valve



ASSEMBLY OF FILTER

44b



FILTER SUB-ASSEMBLY

Fig. 38 - Views 44a and 44b

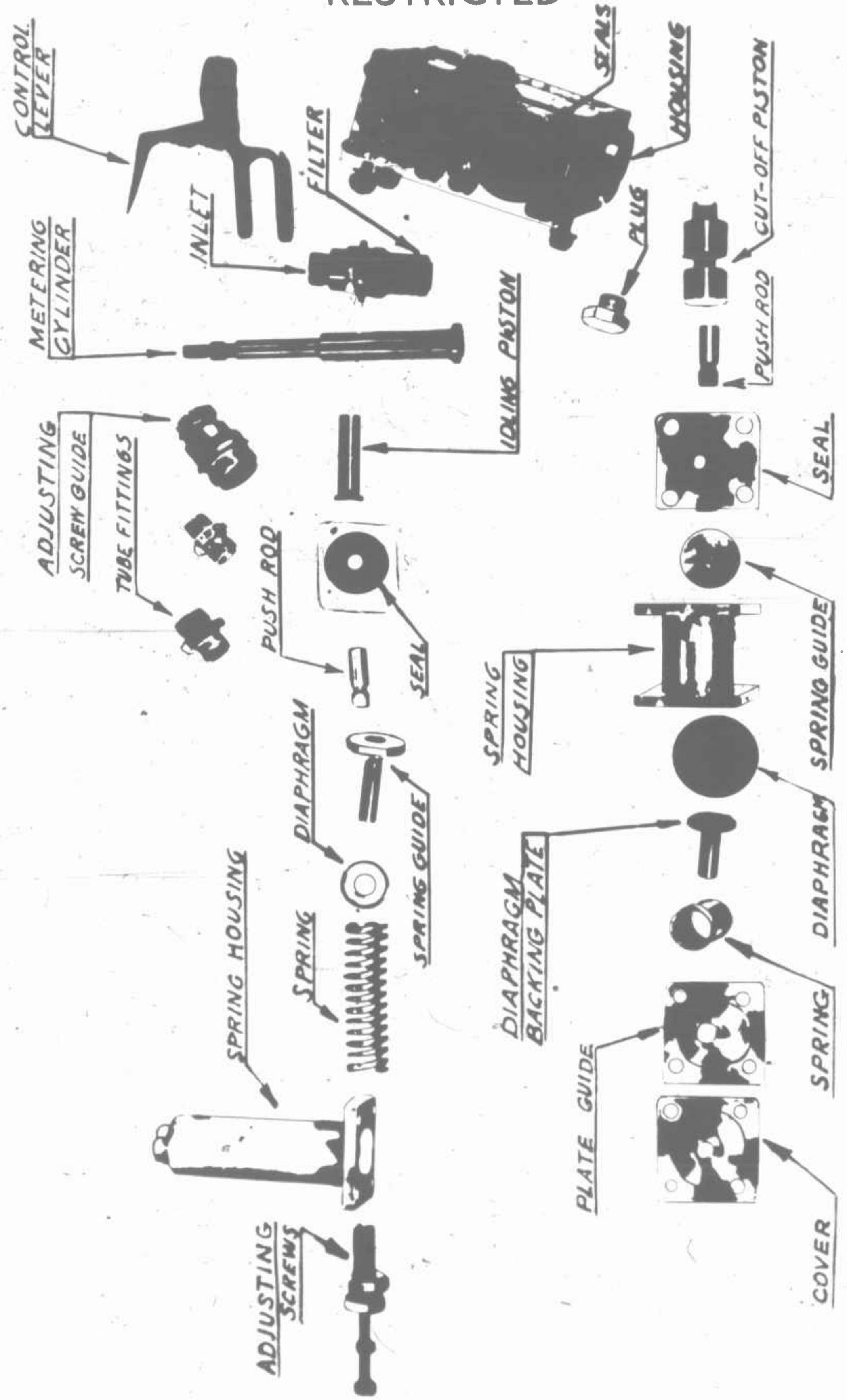
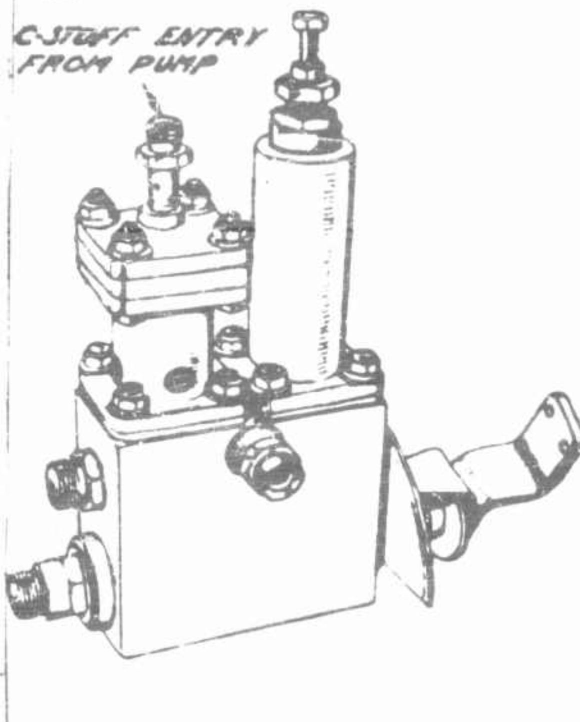


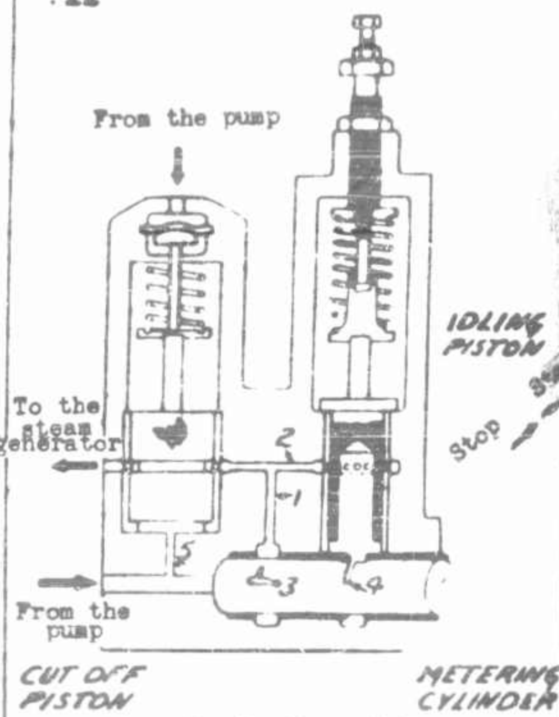
Fig. 30 - Exploded View of T-Stoff Throttle for Steam Generator

.27



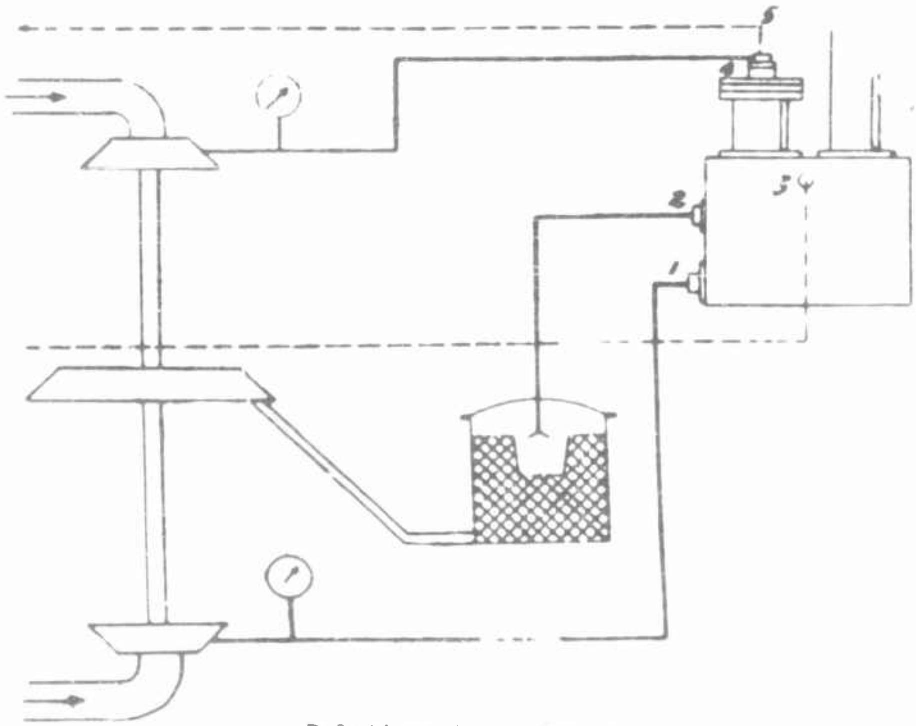
Steam Generator Throttle Assembly

.22



Schematic Section of Steam Generator Throttle

32



Relationship to System

Fig. 40 - Views .27, .22, and .32

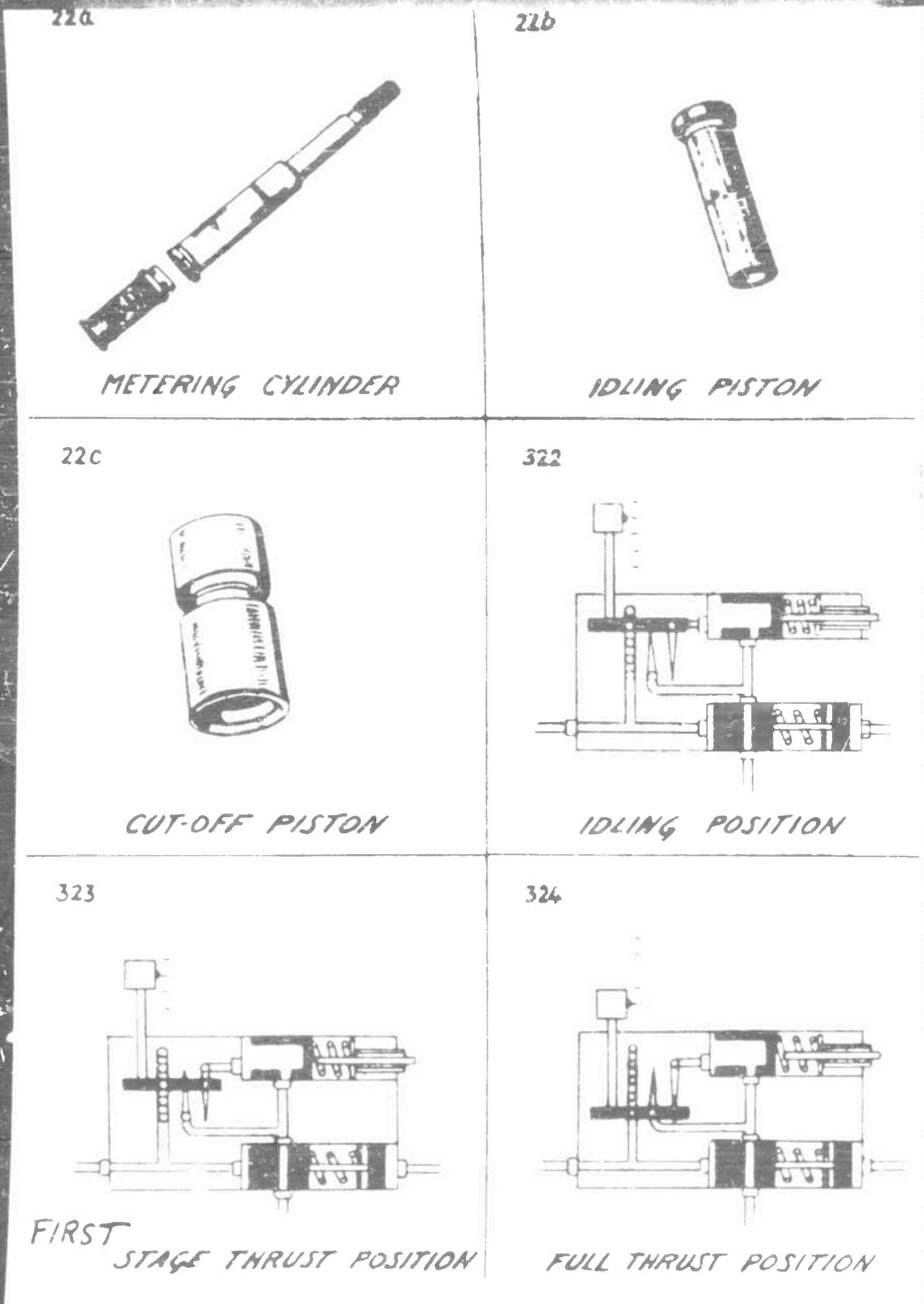


Fig. 41 - Views .22a, .22b, .22c, .322, .323, and .324.

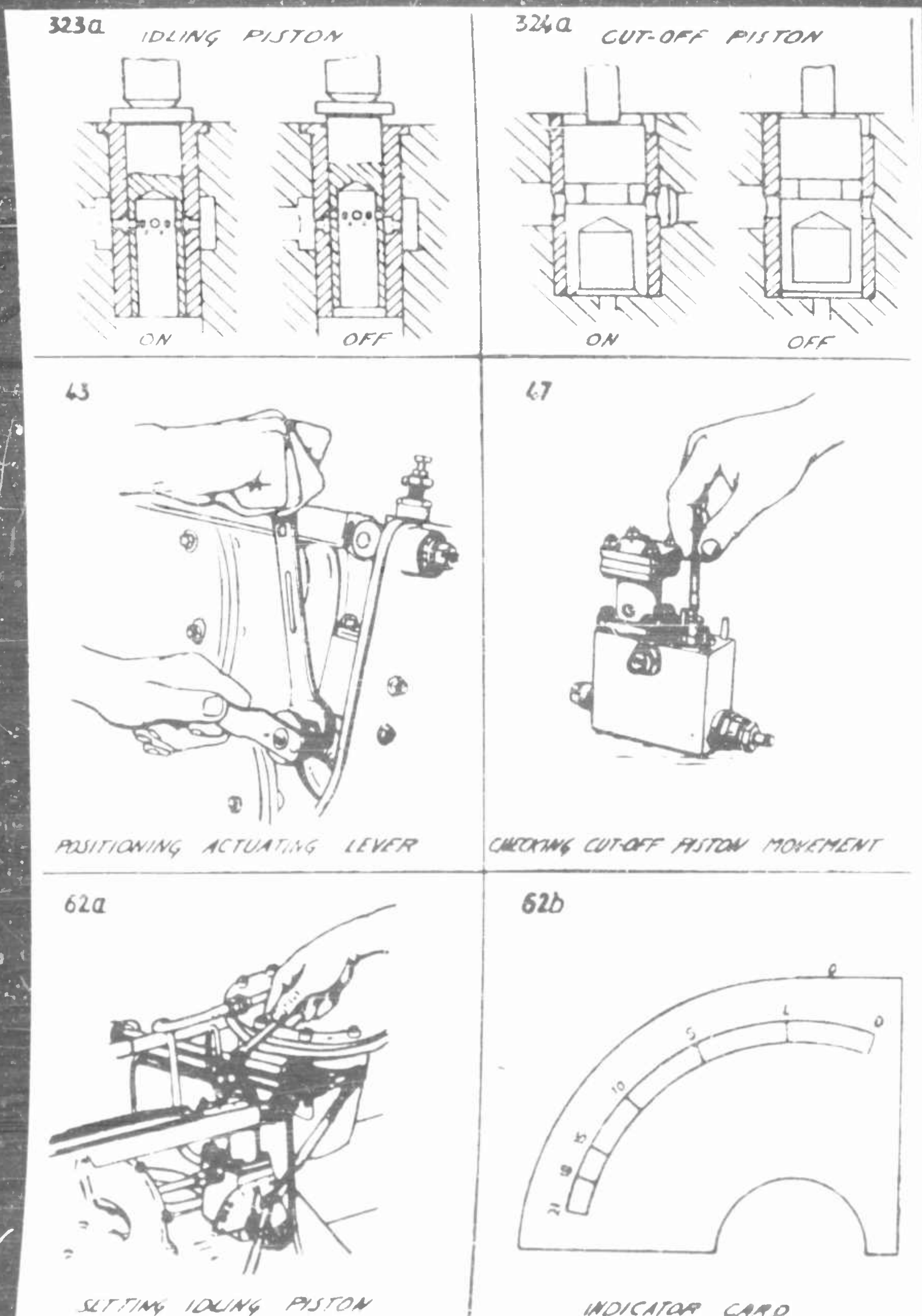


Fig. 42 - Views .323a, .324a, .43, .47, .62a, and .62b

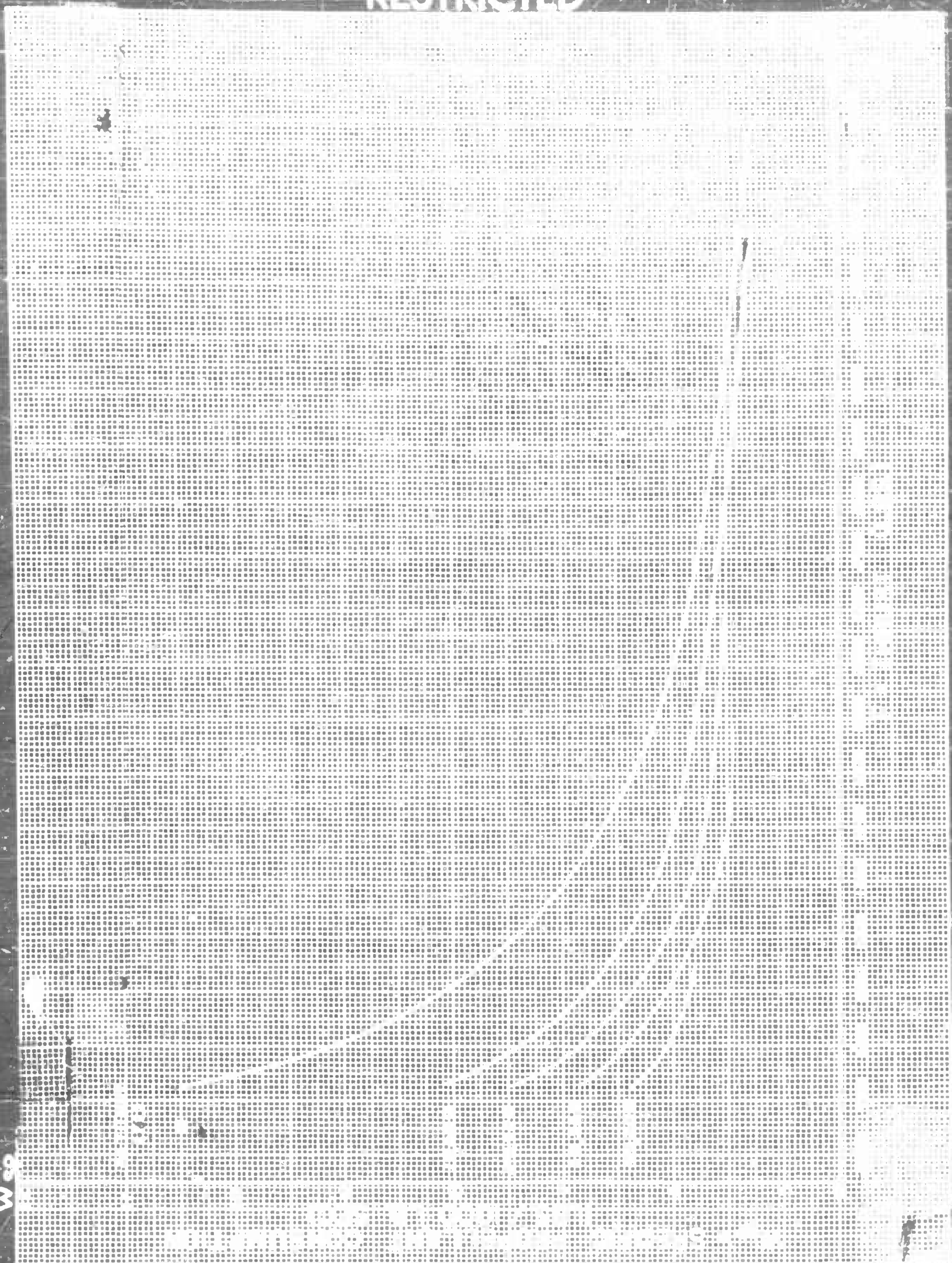


Fig. 43 - Specific Propellant Consumption vs. Thrust at Various Altitudes for 109-509A-1

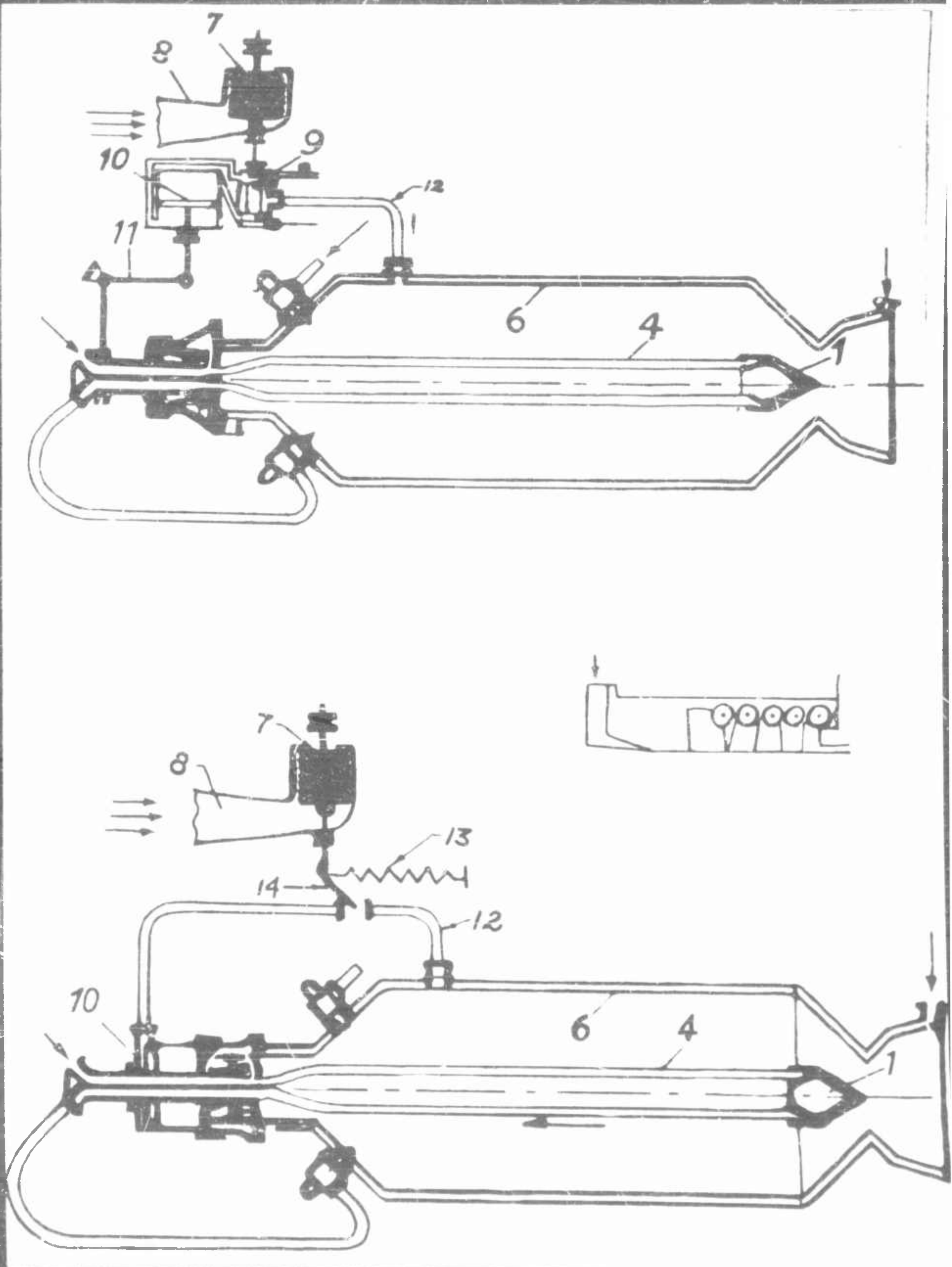


Fig. 45 - Two-Stage Thrust Control Proposal - BMW

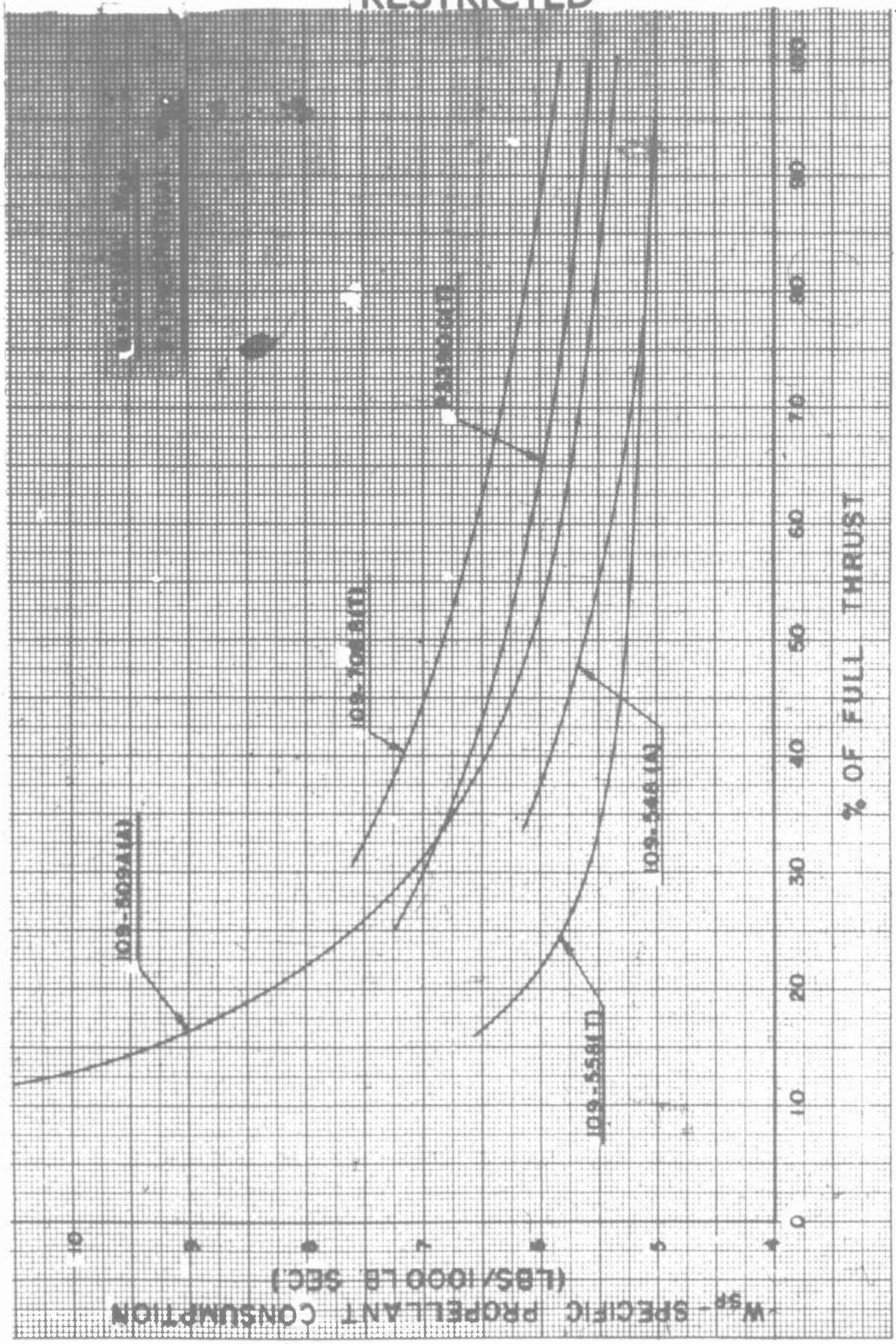


Fig. 46 - W_{sp} as a Function of Throttling (Sea Level)

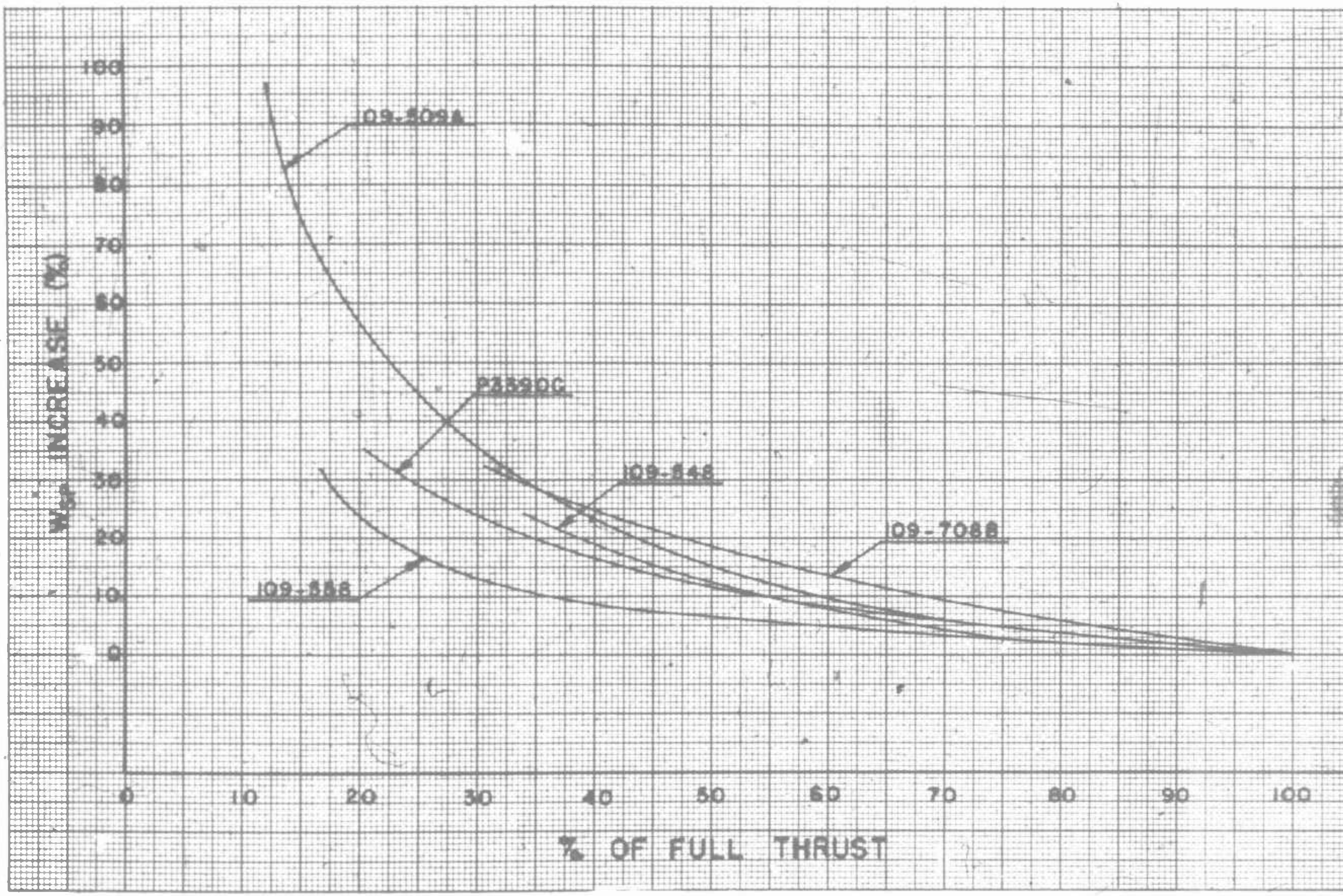


Fig. 47 - W_{sp} Increase as a Function of Throttling (Sea Level)

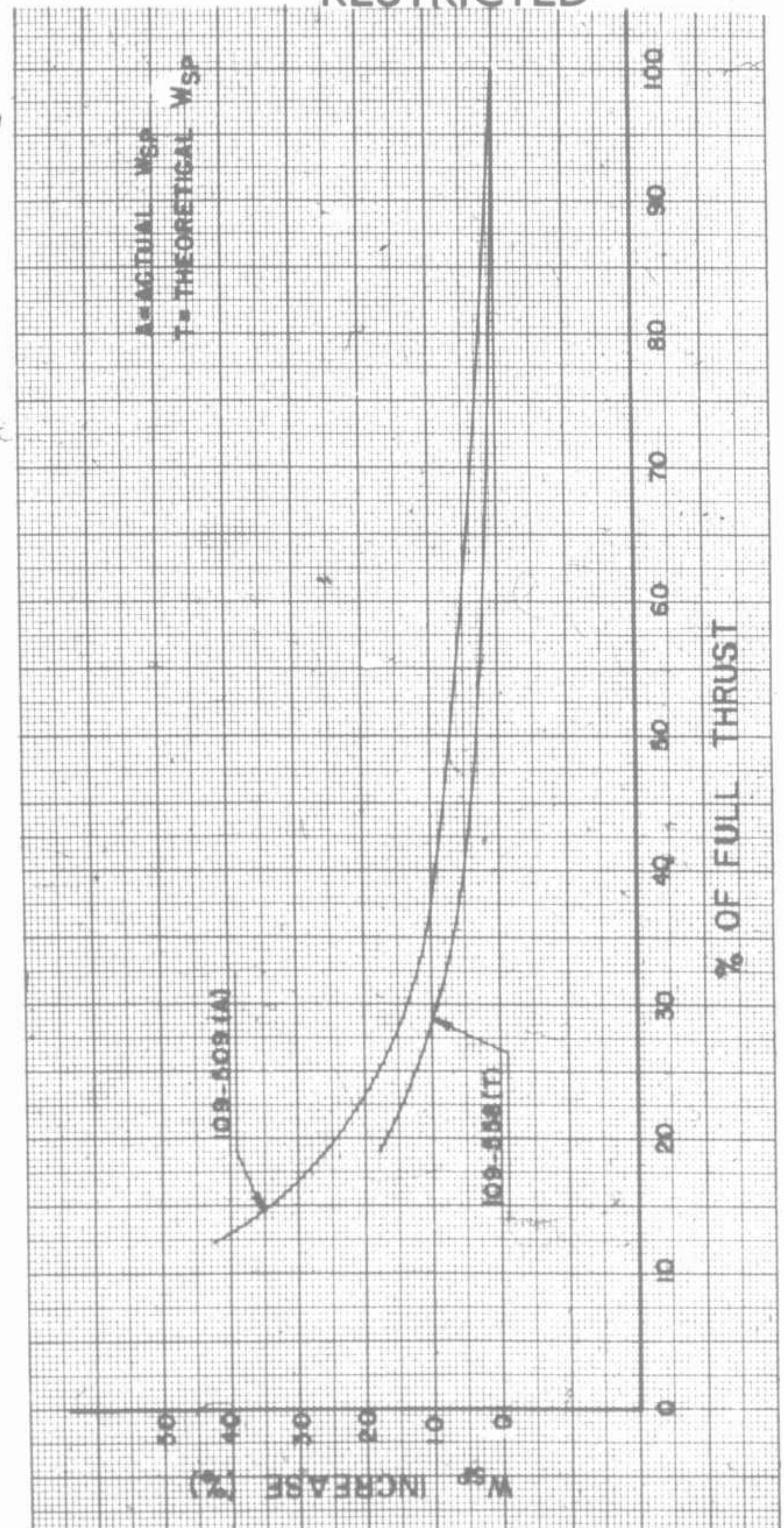


Fig. 48 - W_{sp} Increase as a Function of Throttling (30,000 ft)

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ANALYSIS AND EVALUATION OF GERMAN ATTAINMENTS AND RESEARCH IN THE LIQUID ROCKET ENGINE FIELD - VOLUME VII - THRUST CONTROL - JAN 1951

JAN '51 111PP. PHOTOS, GRAPHS

AMC, WRIGHT-PATTERSON AIR FORCE BASE, DAYTON, O., USAF CONTR. NOS. W33-038-AC-17485 AND AF33(038) 3636 (F-TR-2251-IA)

GUIDED MISSILES(1) ENGINES, ROCKET - GERMANY
PROPULSION(3) ENGINES, ROCKET - CONTROL SYSTEM

and 4-12

CFSTI, auth: ATD ltr, 12 Sept 68

AD-A800 132

U auth: DF fr Air Technical Intelligence Center
dd 1 Sept 54 (21 Sept 54)

* THRUST VECTOR CONTROL SYSTEMS
ROCKET ENGINES

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